Observation of WW+WZ production in a semileptonic decay at CDF

Martina Hurwitz
University of Chicago

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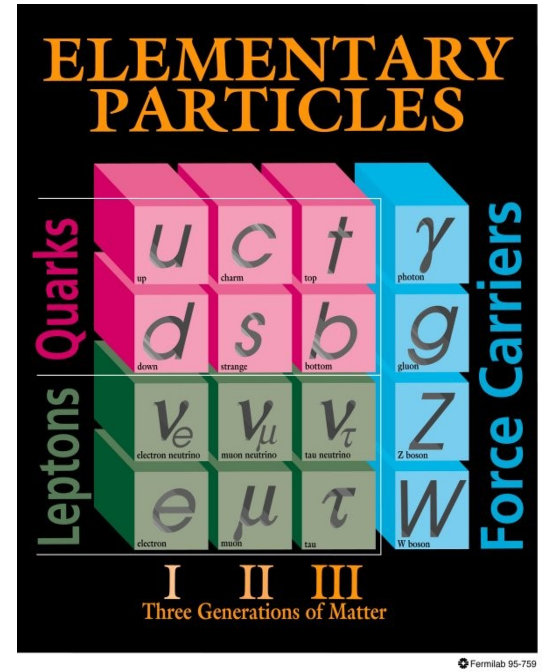
Outline

- Motivation for diboson measurements: Higgs search at Tevatron
- WW+WZ in lepton + jets
  - Event selection
  - Background modeling
  - Matrix element analysis
  - Likelihood fit and systematics
  - Results

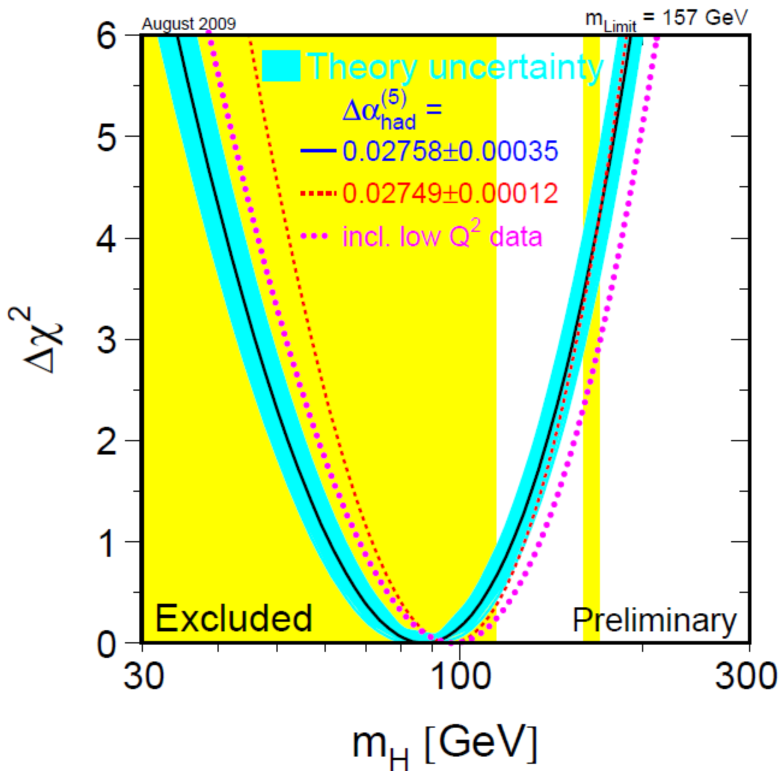
Standard Model Higgs Boson

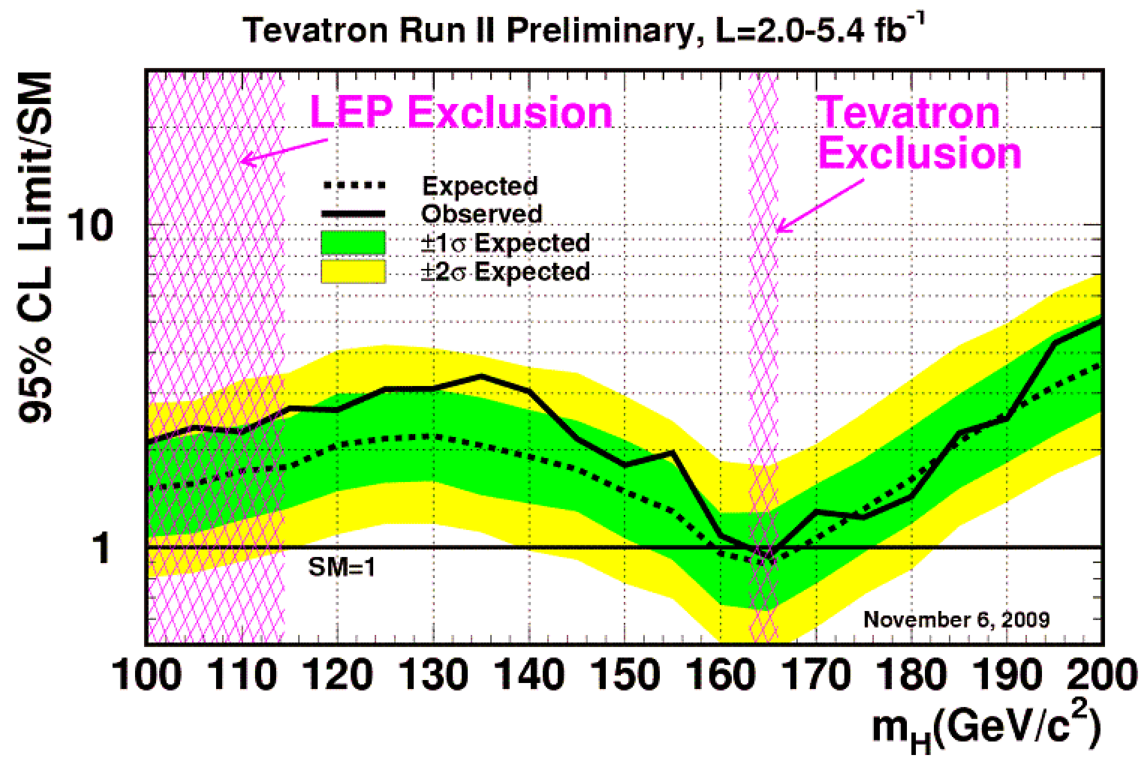
- Standard Model
  - Fermions: six leptons and six quarks
  - $SU(3) \times \underbrace{SU(2) \times U(1)}_{\text{Electroweak theory}}$ gauge group



- $m_\gamma = 0$, $m_W \sim 80$ GeV, $m_Z \sim 90$ GeV
  - Electroweak symmetry is broken
- Higgs mechanism
  - W, Z acquire masses from degrees of freedom of field
  - Fermions acquire masses through Yukawa coupling with field
  - Predicts existence of Higgs boson

What do we know about the Higgs?

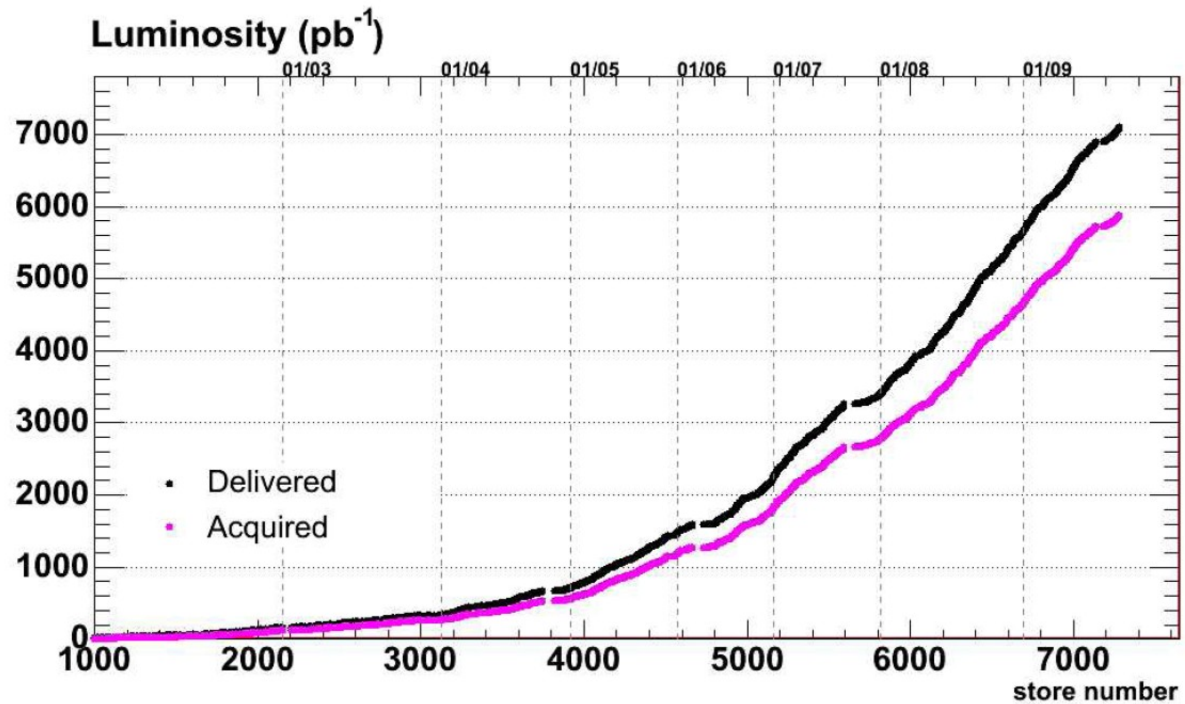




- Direct search at LEP: m_H > 114 GeV
- Indirect searches (through radiative corrections to W mass): m_H < 157 GeV
- Tevatron contribution: ~~163 < m_H < 166~~

All at 95% C.L.

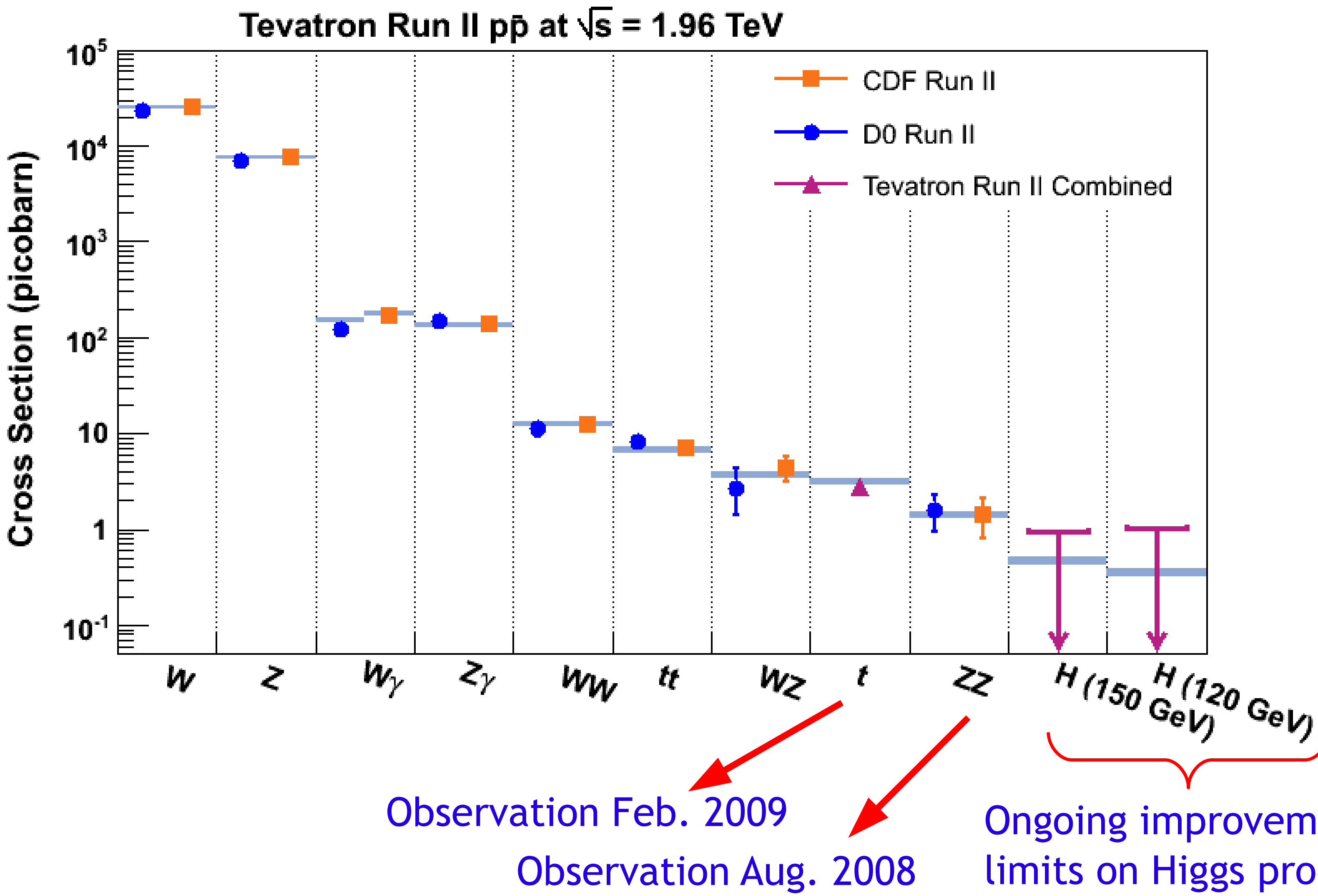
Tevatron



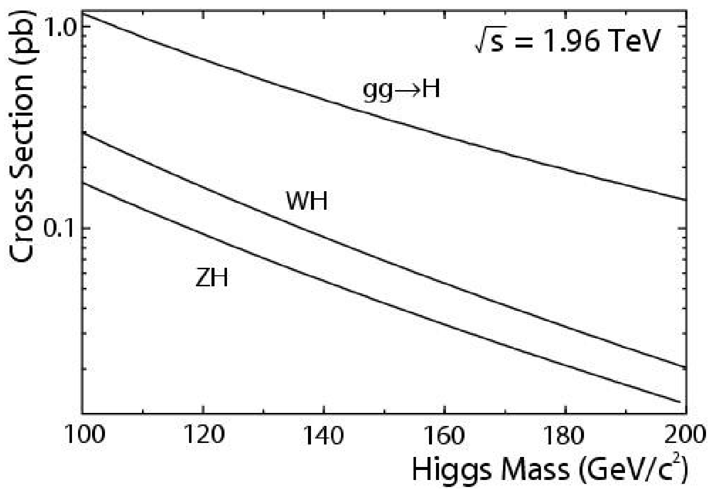
- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Stable operation over last several years → large datasets

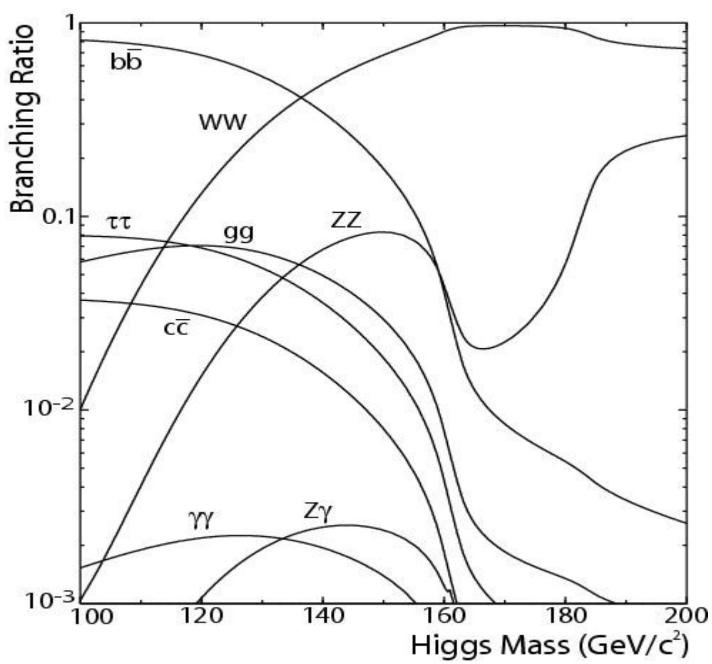
Progress at the Tevatron

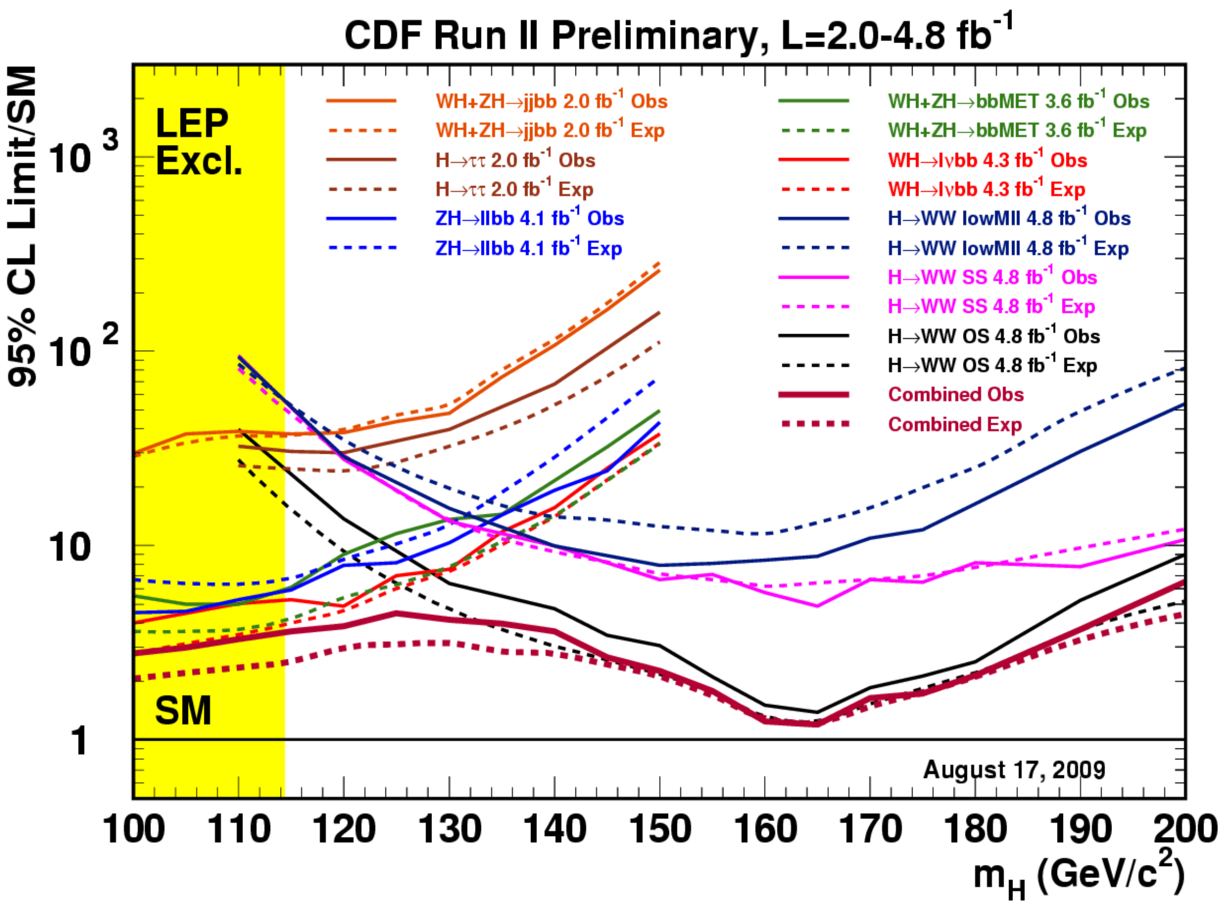
Larger datasets → probe smaller cross sections



What goes into the Higgs limit?

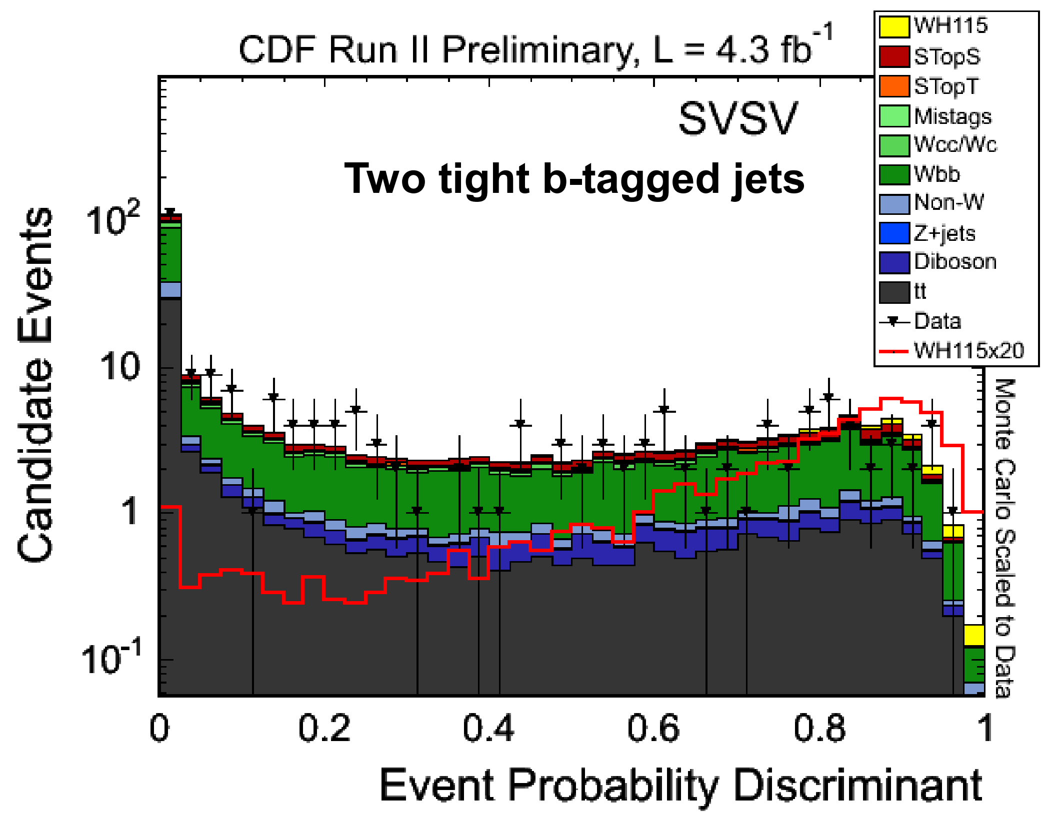






Example: WH → lνb$\bar{b}$ at CDF

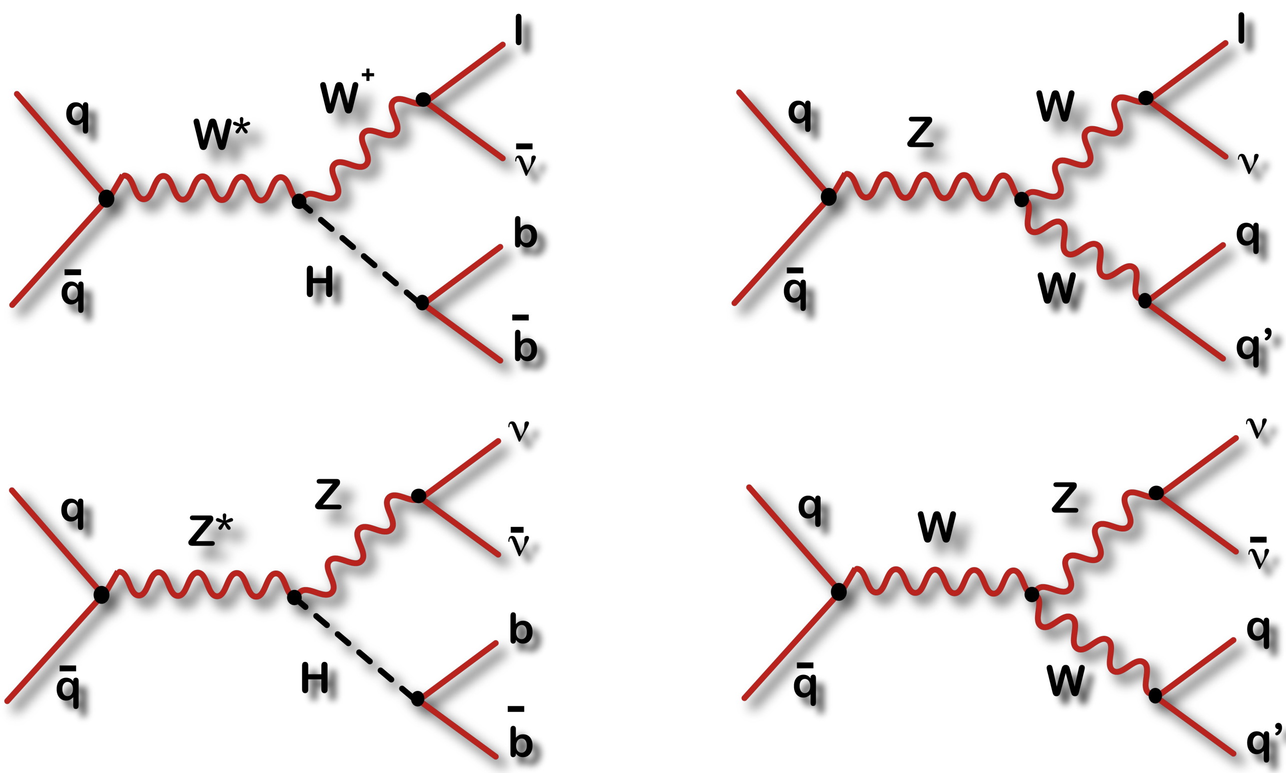
- Sensitive channel at low mass: identified lepton and b-tagging effectively reduce backgrounds
- Sensitive analysis includes
  - High signal acceptance (e.g. add new triggers)
  - Multivariate techniques: matrix element and neural network
  - Separation of channels according to different signal-to-background ratios (e.g. two b-tagged jets vs 1 b-tagged jet)



A lot of sophisticated techniques are used in the Higgs limits. Prove we understand them by measuring known processes.

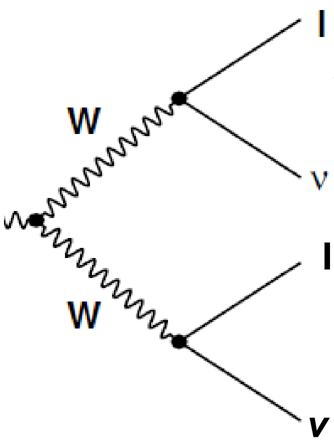
Higgs → "Dibosons"

- In this talk, "dibosons" = WW, WZ
  Semileptonic = one boson decays to quarks, the other to leptons
- Semileptonic diboson decays have similar topology to sensitive channels in low-mass Higgs search



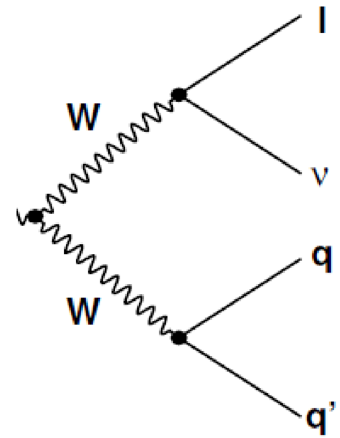
- Similar experimental challenges
- Important difference: No b-tagging (yet)

Diboson measurements at Tevatron



Fully leptonic decays

- Both bosons leptonic: W→lν, Z→ll or Z→νν
  - Low branching ratios, but "clean" signatures at a hadronic collider



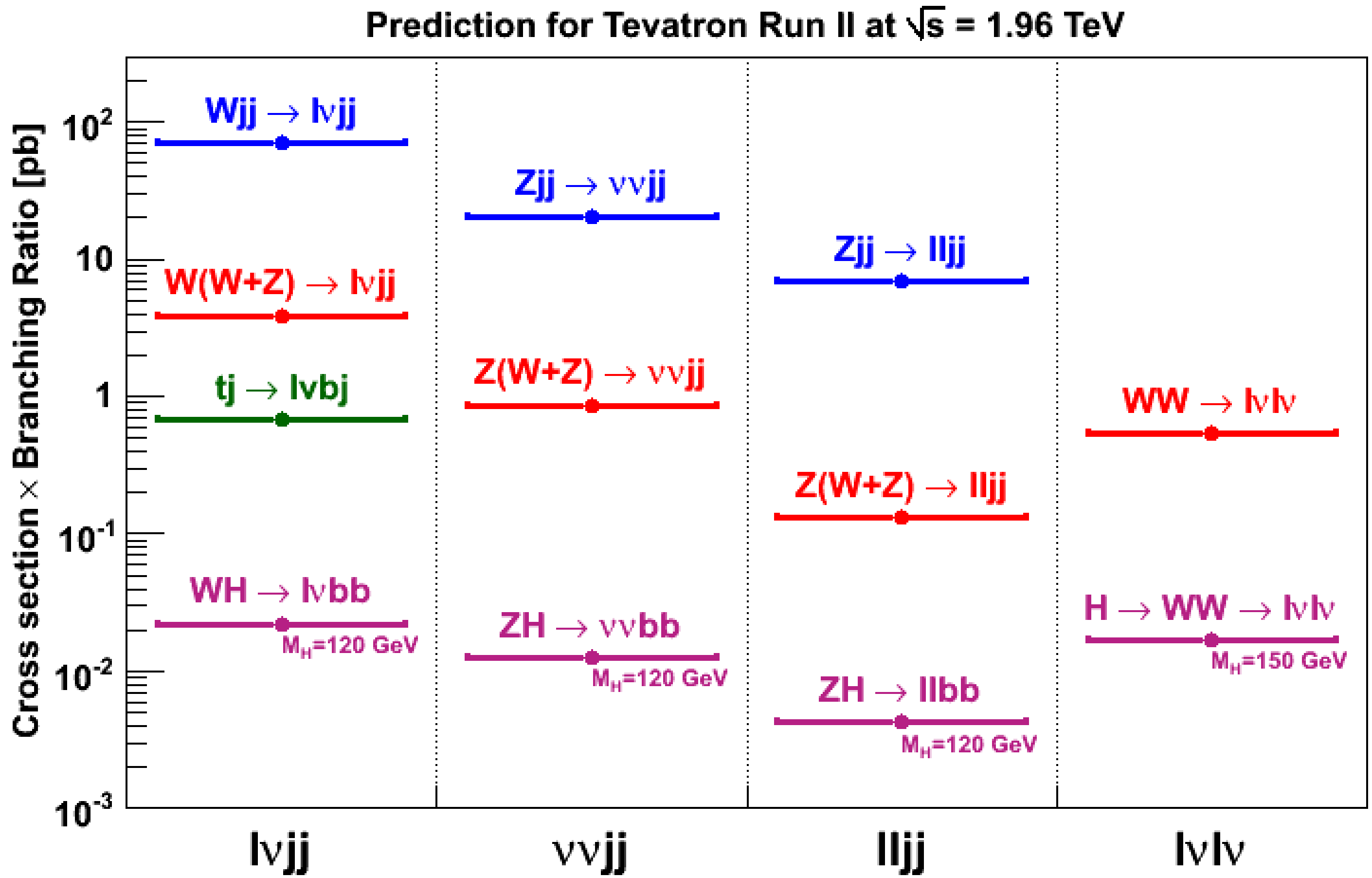
Semileptonic decays

- One boson hadronic: W→qq', Z→$q\bar{q}$
  - Higher branching ratios but large backgrounds

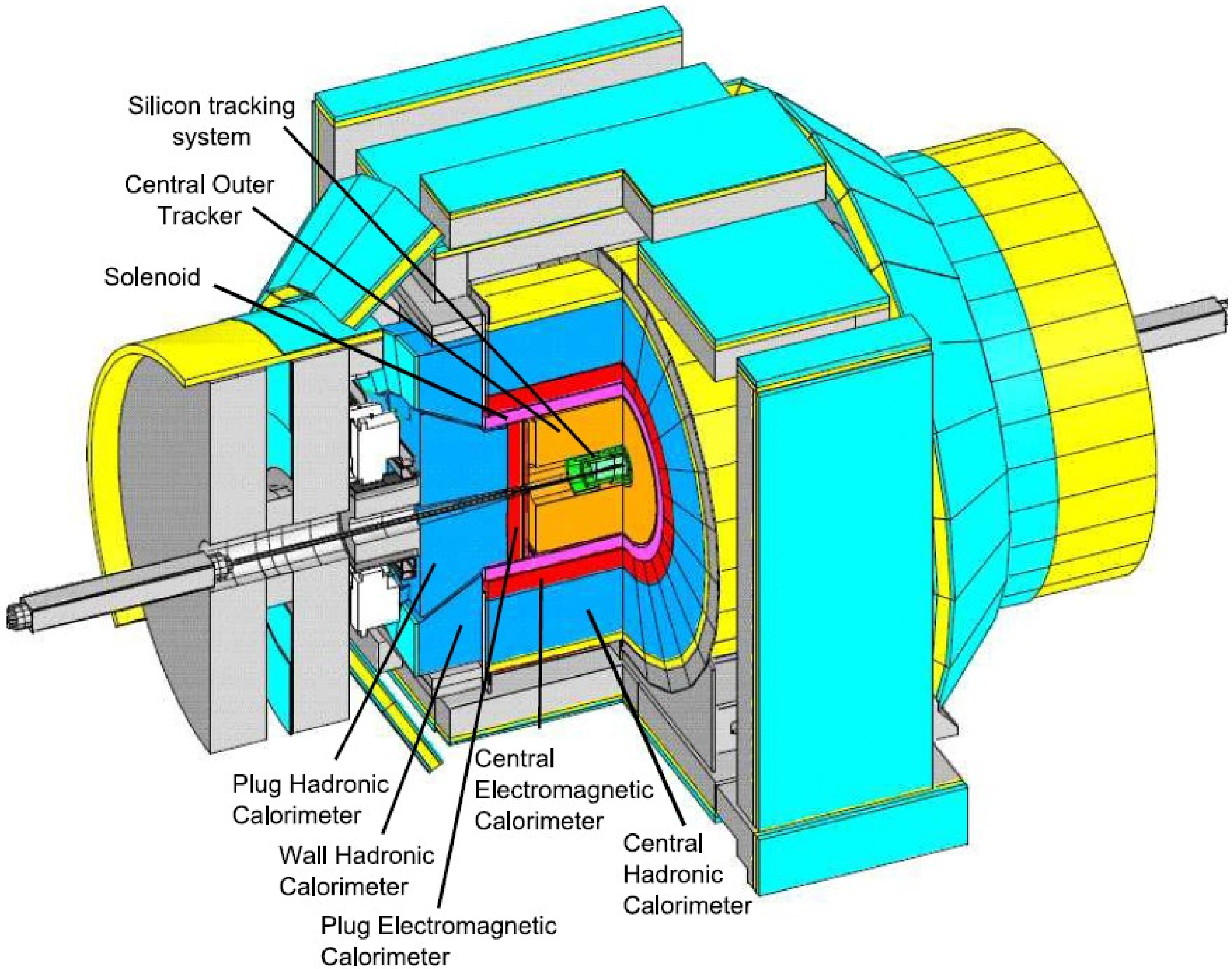
- WW, WZ, ZZ in leptonic modes have been observed at the Tevatron
  - Cross sections in good agreement with Standard Model predictions
  - Set limits on new physics contributing to TGCs

- Recent results
  - First observation in channel with large missing energy and jets (CDF)
  - **Observation in channel with identified lepton and jets (CDF)**
    - Previously evidence (D0)
  - Limits on TGCs (D0)

Higgs and diboson rates

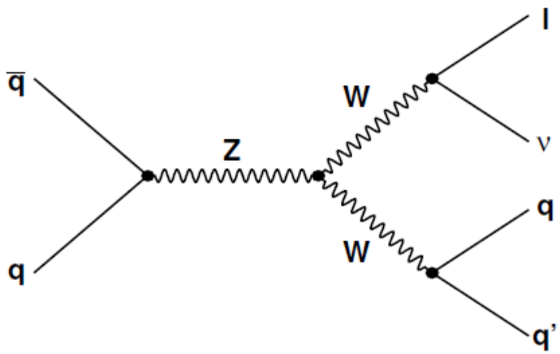


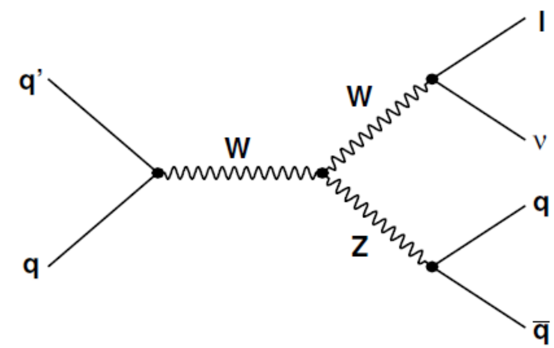
Apparatus: CDF detector

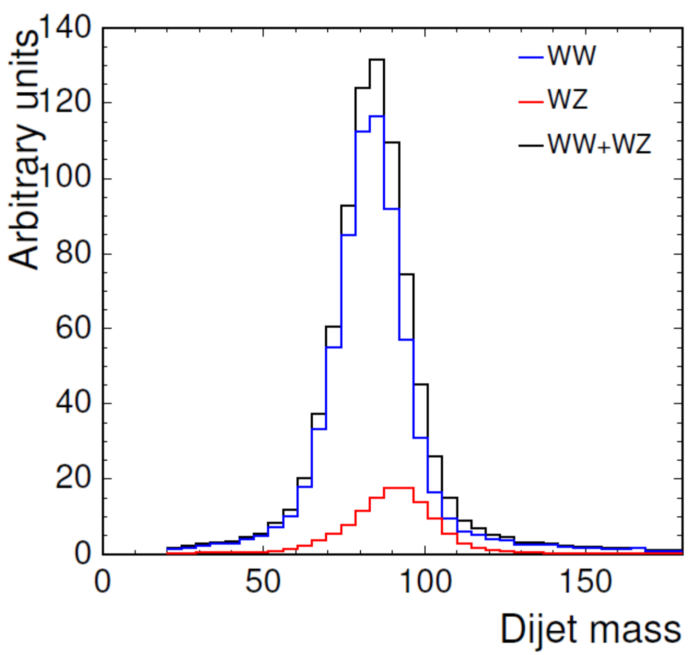


Dataset: 4.6 fb^{-1} collected through summer 2009

WW+WZ → lvjj





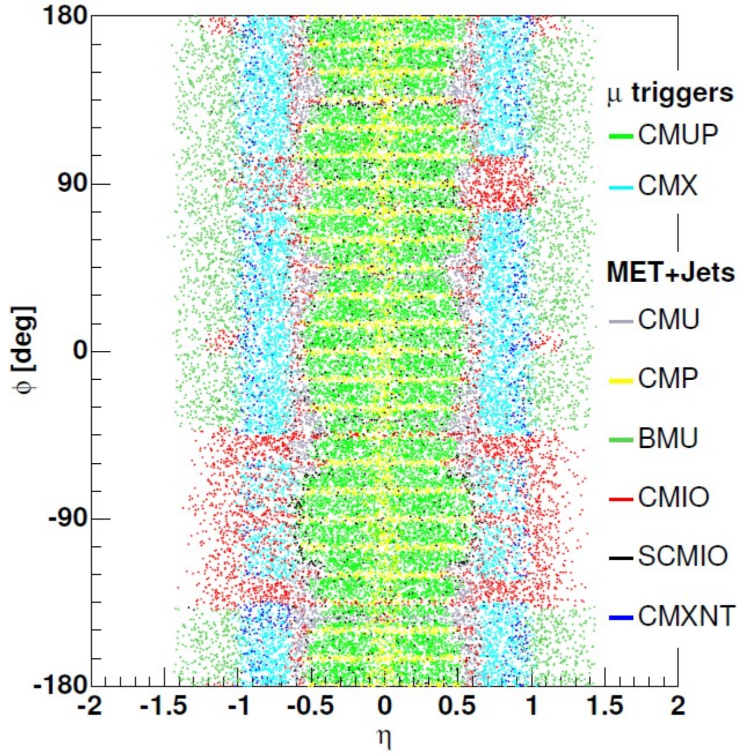


- High p_T isolated electron or muon + two jets + large missing transverse energy
- Signal has dijet resonance
  - We don't try to distinguish W→jj from Z→jj
  - From σ*B.R., expect ~85% of signal from WW

Triggers

Trigger

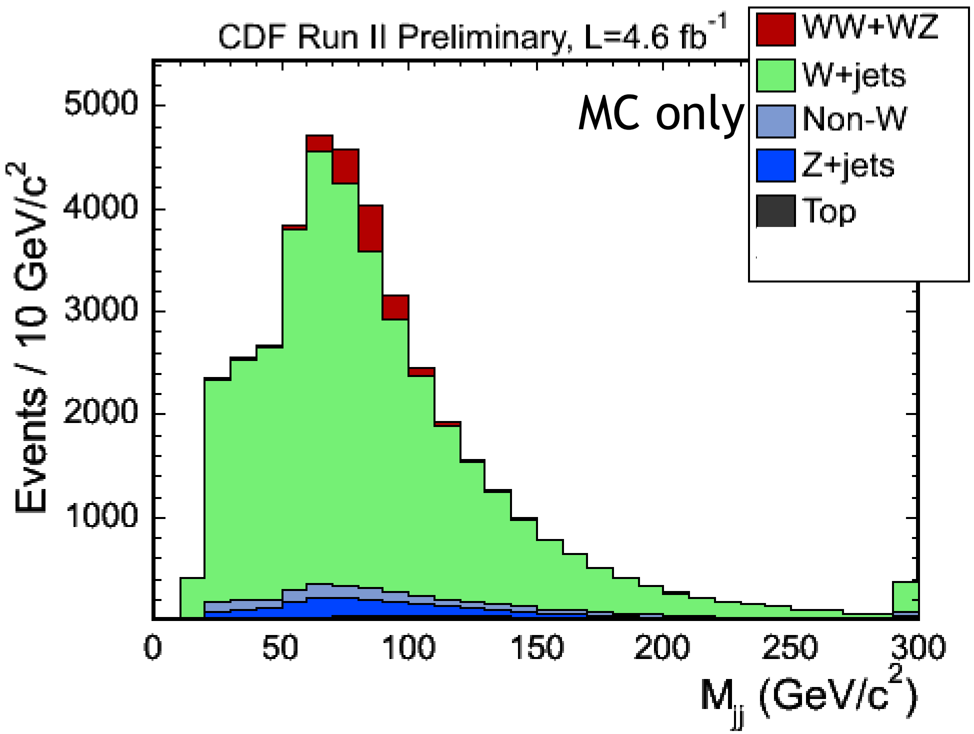
- High p_T central electron and muon triggers
- Thanks to efforts in Higgs and single top searches → MET + jets trigger improves muon acceptance



- Three channels: central electrons, central muons, extended muons

Backgrounds

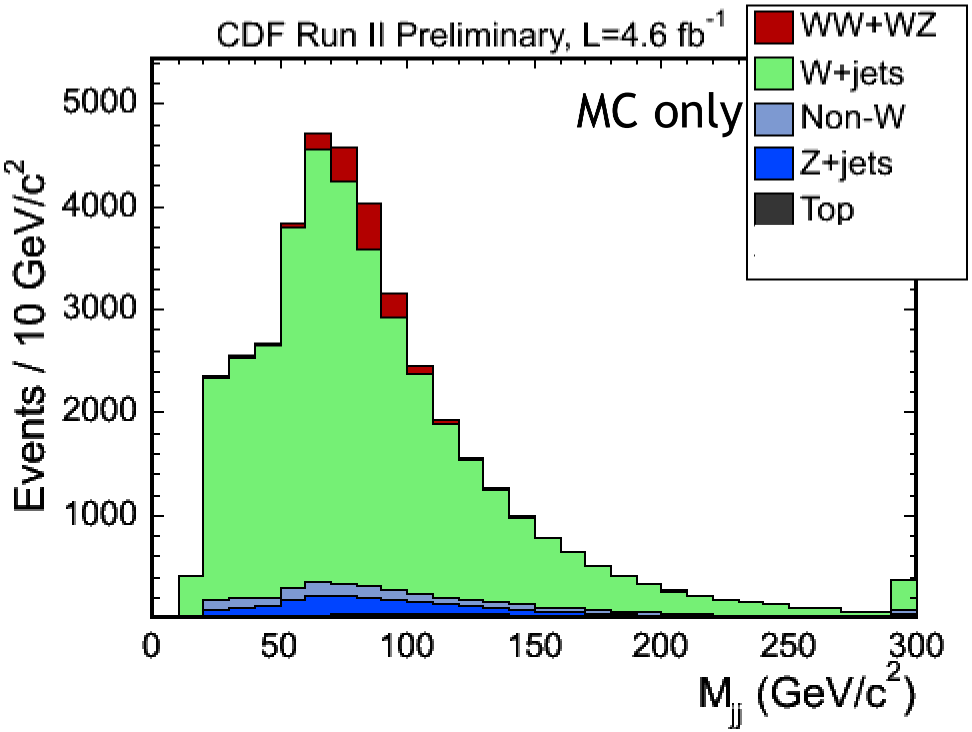
- W+jets: similar to signal → large
- QCD multi-jet (non-W): jet fakes a lepton and there is large fake MET → fairly small, reduce with vetos on transverse mass of leptonic W candidate, angles of MET and jets
- Z+jets: miss a lepton → small, reduce with veto on additional leptons
- $t\bar{t}$: miss a lepton or a few jets → small, reduce with veto on additional jets
- Single top: small



Background modeling

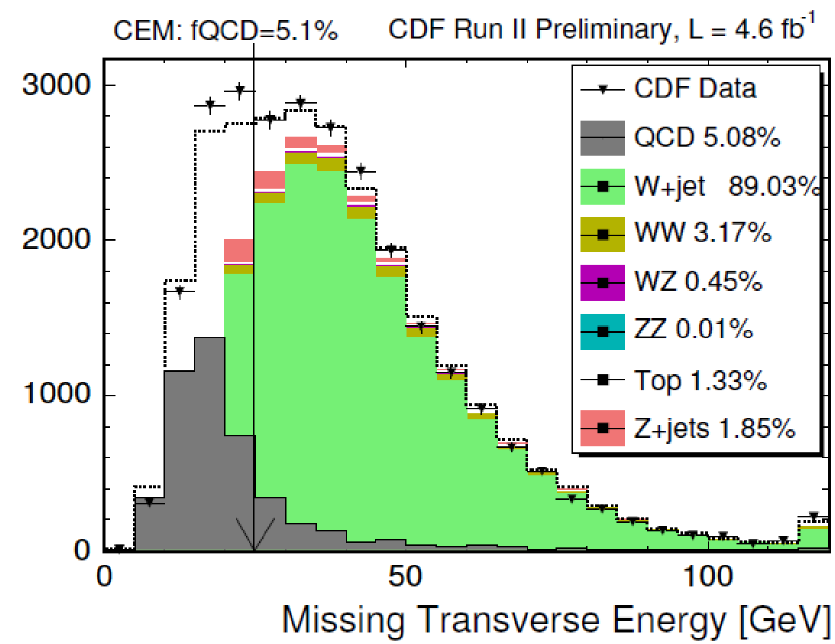
We need to understand the normalization and kinematics of the backgrounds: use MC modeling

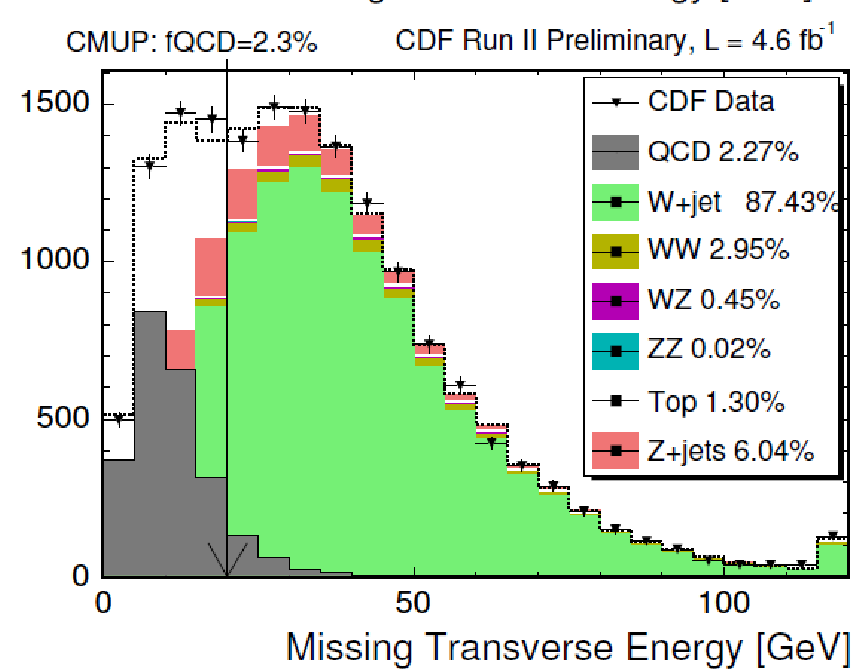
- W/Z+jets: Alpgen + Pythia
- QCD multi-jet: data with loosened lepton selection
- Signals and top backgrounds: Pythia



Background normalization

- How many background events enter our sample?
  - Dependent on background's production cross section, selection efficiency, and luminosity
- MC-driven: Z+jets, tt, single top
  - Trust theoretical/measured cross sections and Monte Carlo models
- Data-driven: QCD multi-jet, W+jets
  - Not clear how to derive normalizations from models
  - QCD multi-jet: from fit to MET spectrum
  - W+jets: preliminary estimate from MET fit





Expected event yields

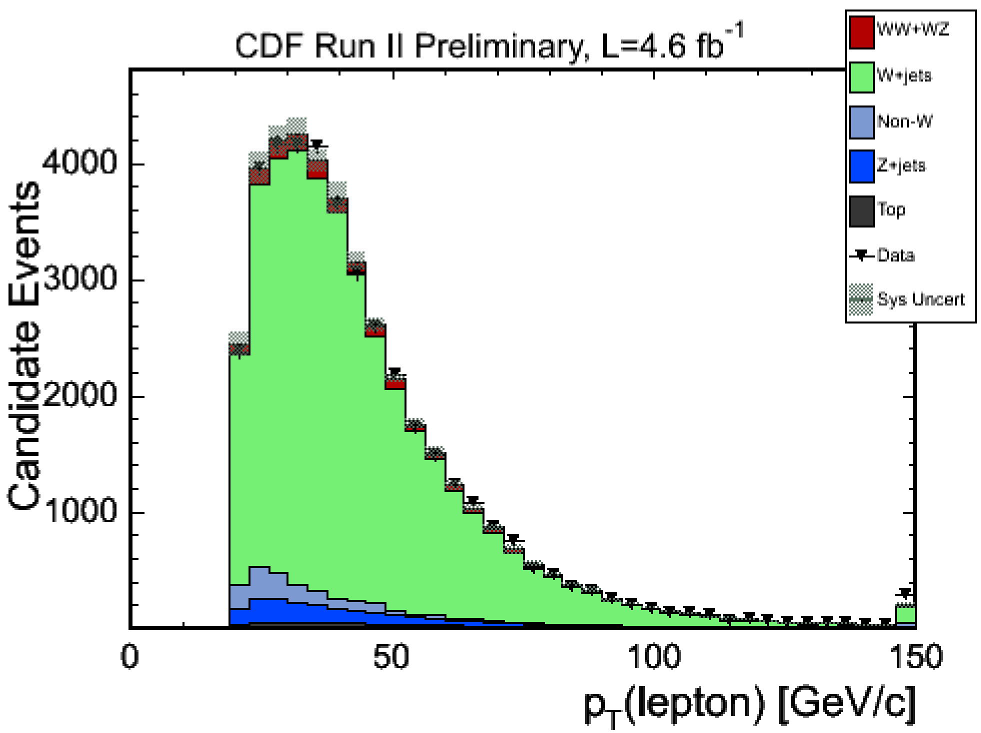
Process	Central electrons	Central muons	Extended muons
WW	591 ± 50	523 ± 51	148 ± 13
WZ	84 ± 9	83 ± 10	29 ± 3
W+jets	16708 ± 394	15774 ± 260	3155 ± 70
QCD multi-jet	959 ± 384	443 ± 177	112 ± 45
Z+jets	304 ± 38	1071 ± 144	325 ± 41
tt	120 ± 17	109 ± 16	64 ± 9
Single top	121 ± 18	108 ± 16	47 ± 7
ZZ	1 ± 0.2	4 ± 0.7	2 ± 0.3

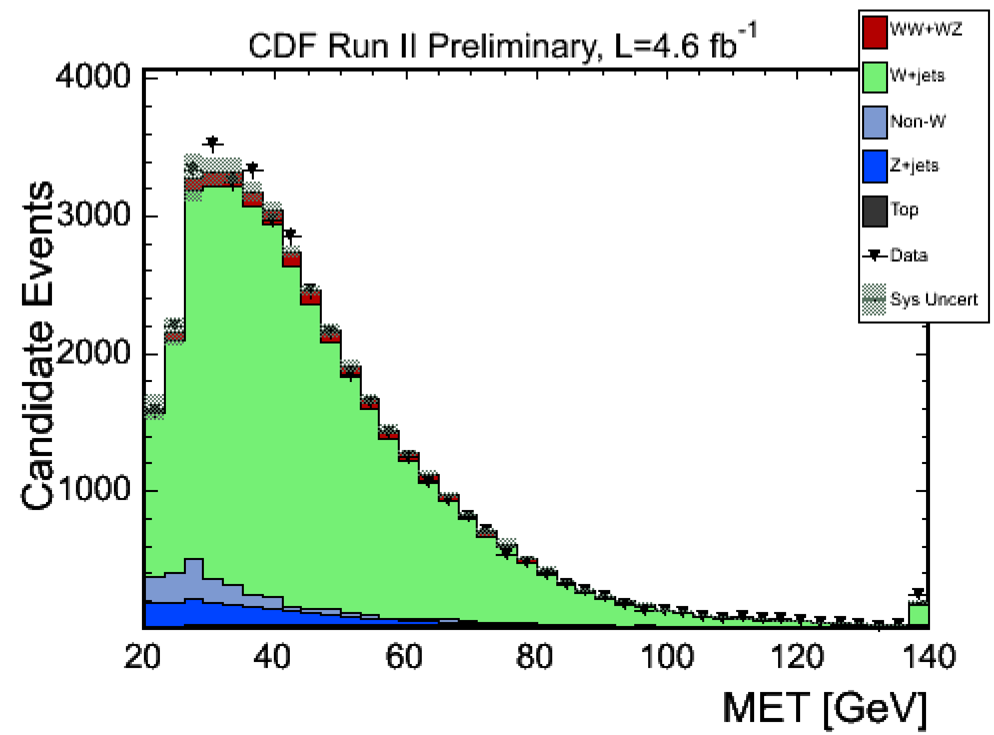
Total predicted signal events: 1458
Total predicted background events: 39427
$S/\sqrt{B} = 7.3$

Background modeling

- Modeling of the shape (kinematics) for the backgrounds (especially W+jets) is crucial
  - They are large
  - We use the modeling to estimate efficiencies of cuts
  - We will use the models to make templates of our discriminant to extract the signal
- Validate modeling of kinematics by comparing data and MC
- Start thinking about systematic uncertainties
  - If we observe mismodeling, is it covered by a systematic?
  - We will impose systematic uncertainties on shape of W+jets discriminant due to
    - Jet energy scale (JES)
    - Factorization and renormalization (Q^2) scale
    - Mismodeling that's not covered by these uncertainties

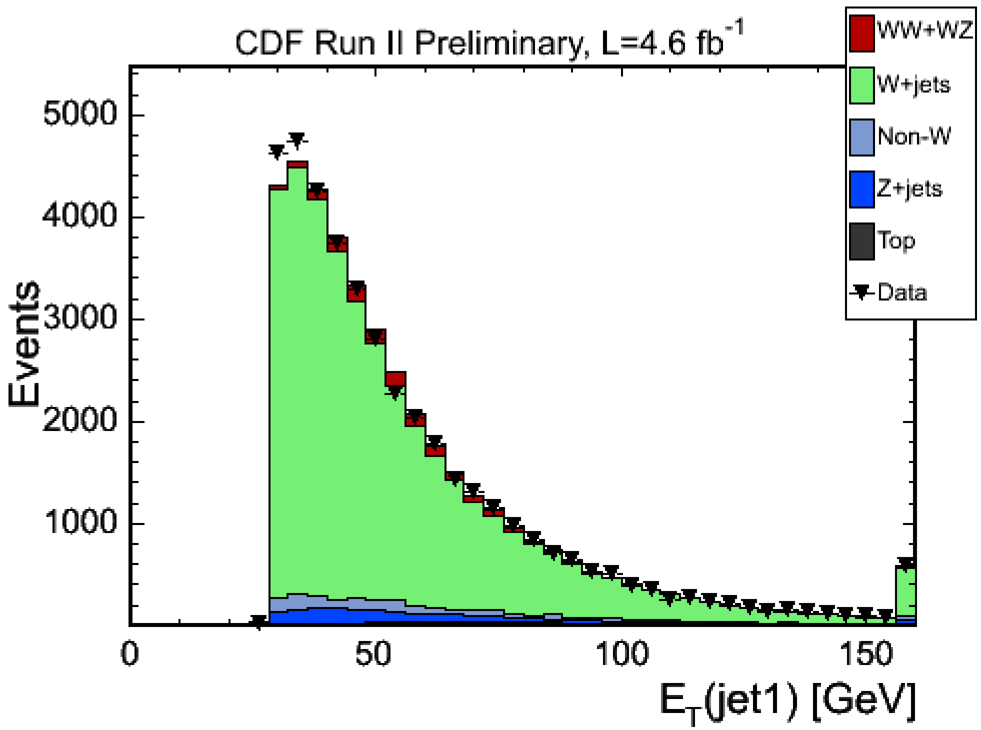
Lepton, MET

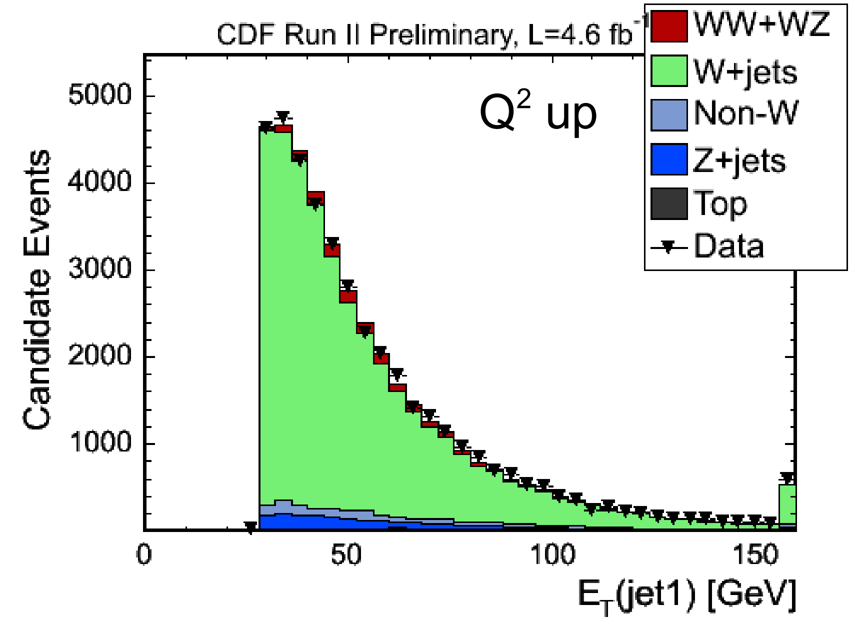


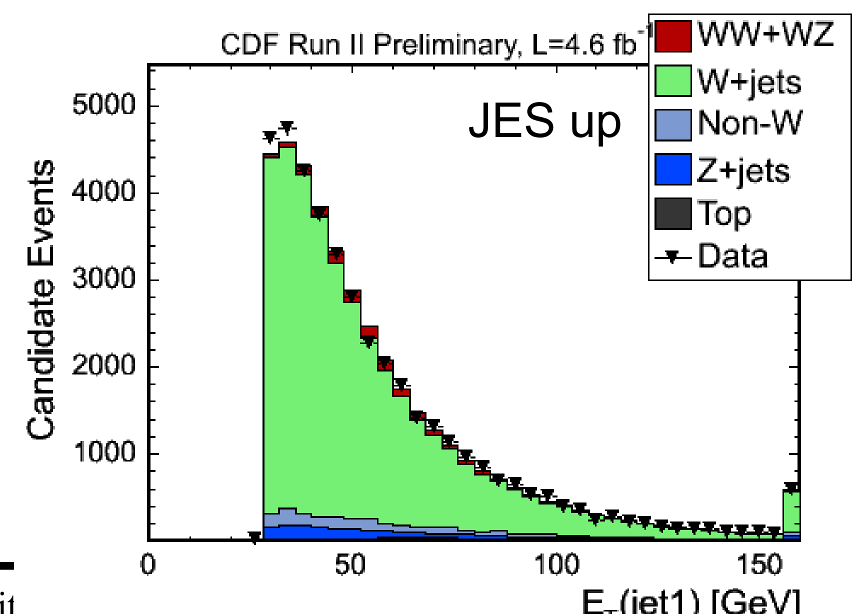


Data / MC agreement is good → QCD multi-jet model is OK

Jet E_T

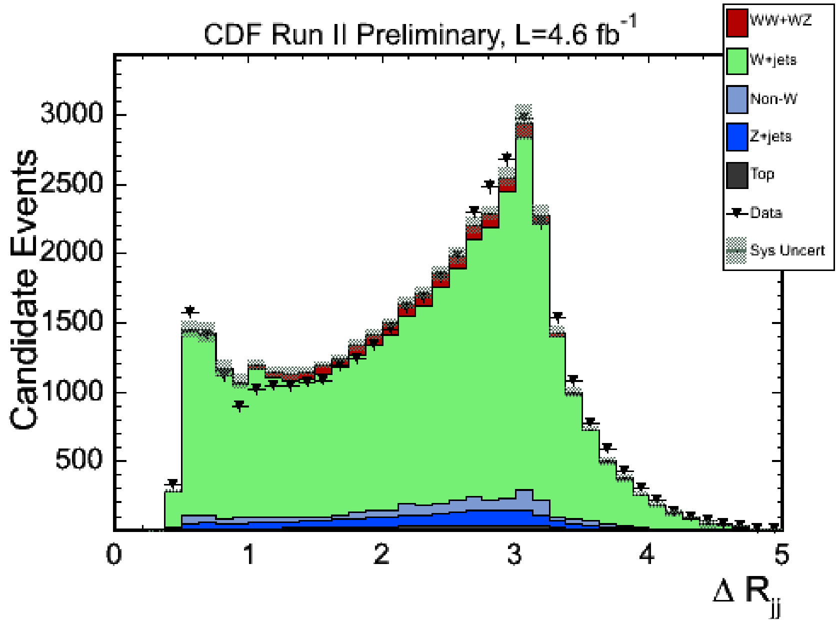


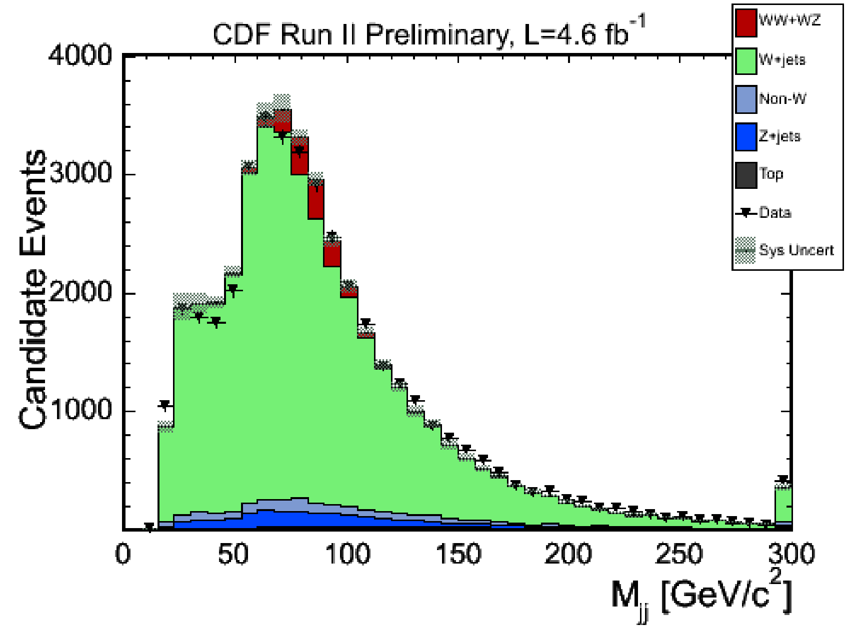


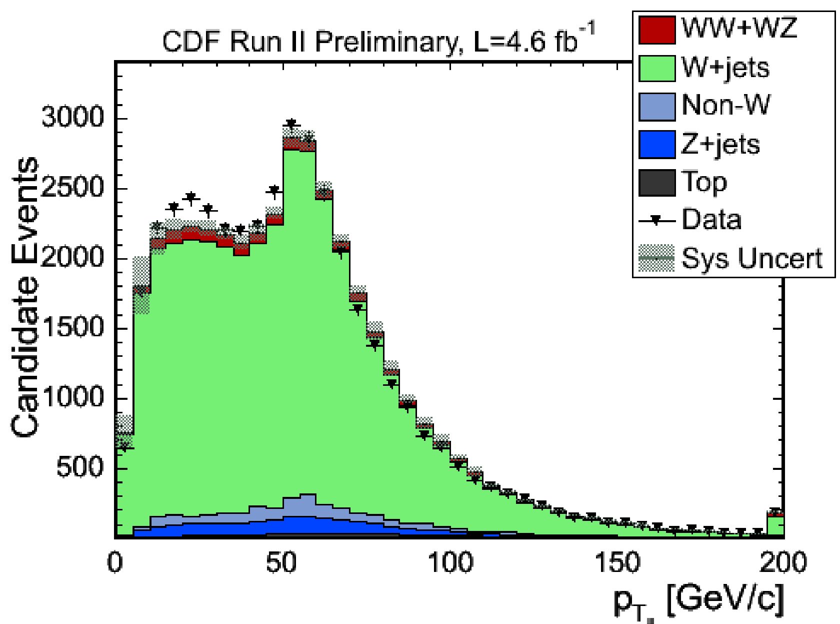


Disagreement between data and MC is covered by JES and Q^2 uncertainty

Dijet modeling





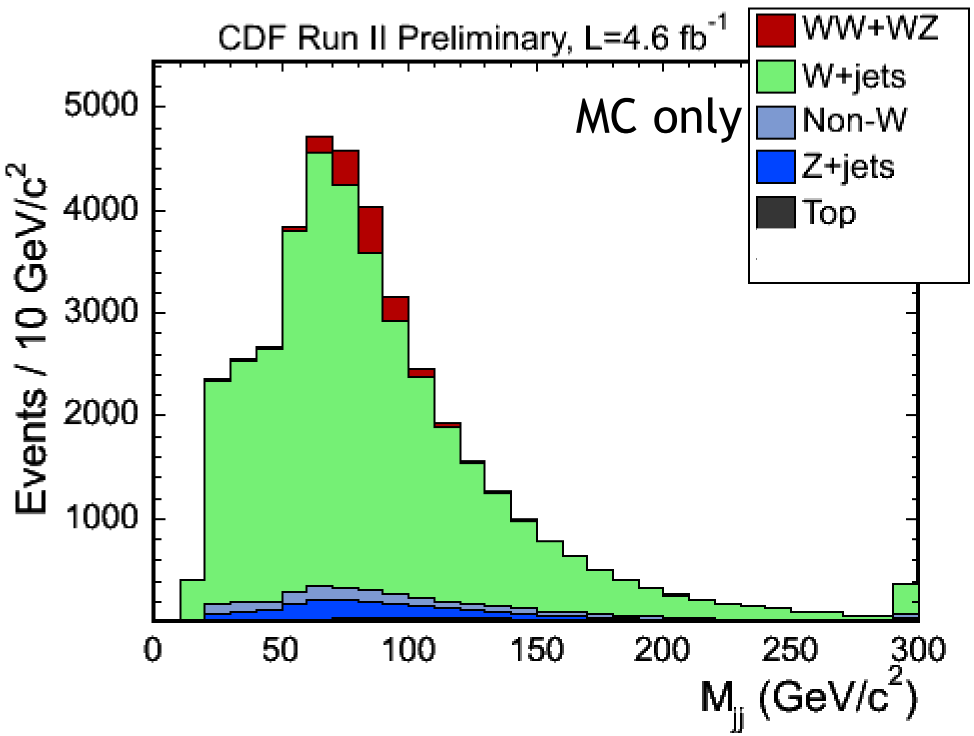


Resonance decaying to two jets is major difference between signal and background

ΔR (angular distance between jets) and M_{jj} (invariant mass) OK within systematic uncertainties

p_{Tjj} not good → introduce additional systematic uncertainty

Matrix elements: why?



- We can improve the sensitivity of the measurement by:
  - Adding information from other event kinematics
  - Building a discriminant that has bins with higher S/B or with larger difference in shape between signal and background
- Matrix element calculations
  - Sensitive technique in WH and single top searches
  - This analysis based on those implementations

Matrix element calculation

Given 4-vectors of incoming and outgoing partons in an interaction, can calculate differential cross section of a certain production process:

$$d\sigma = \frac{(2\pi)^4 |\mathcal{M}|^2}{4\sqrt{(\vec{q_1} \cdot \vec{q_2})^2 - m_1^2 m_2^2}} \times d\Phi_n$$

For each event, determine this differential cross section for signal and background processes

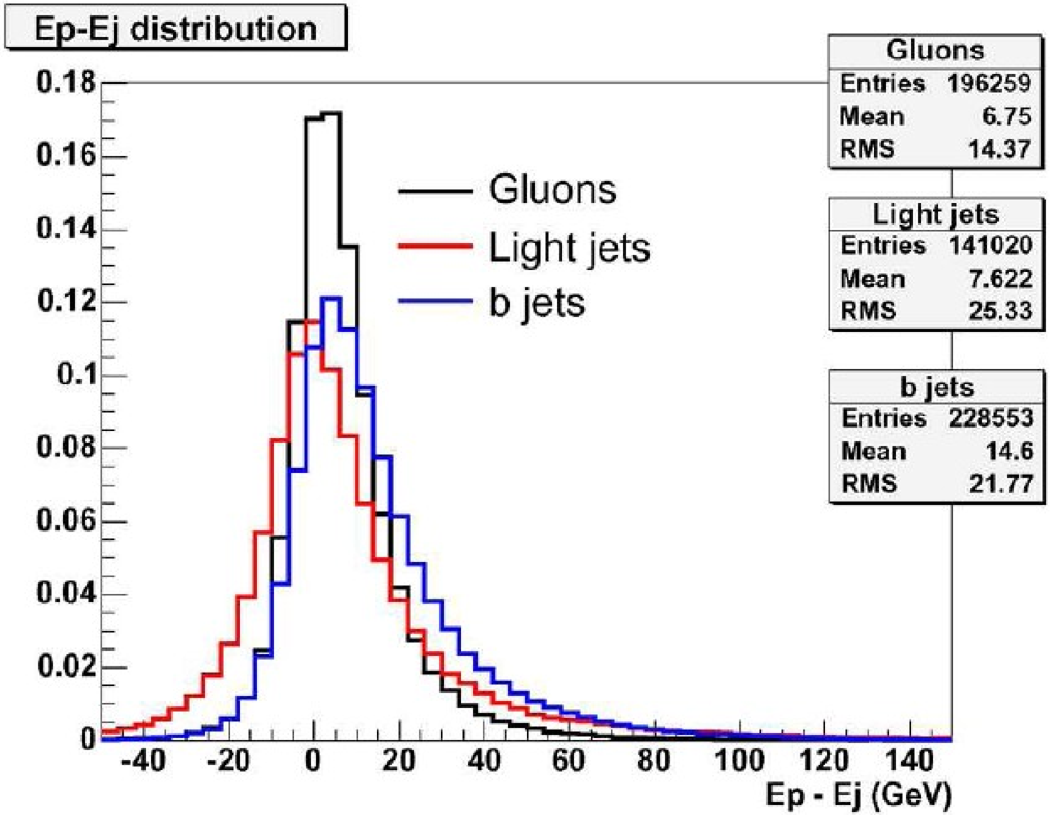
Then define "event probability" (not really a probability): $P \sim \frac{d\sigma}{\sigma}$

But: no way to know initial parton 4-vectors and measurement of final state is not exact → Integrate over unknowns

$$P(x) = \frac{1}{\sigma} \int d\sigma(y) \underbrace{dq_1 dq_2 f(q_1) f(q_2)}_{\text{Initial state: Parton distribution functions}} \underbrace{W(y,x)}_{\text{Final state: transfer function}}$$

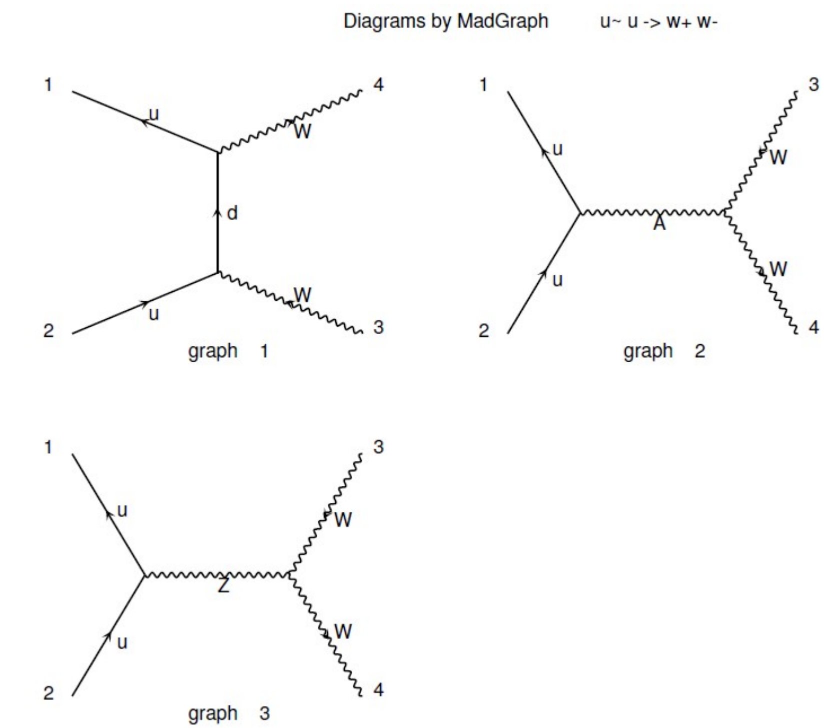
Transfer function

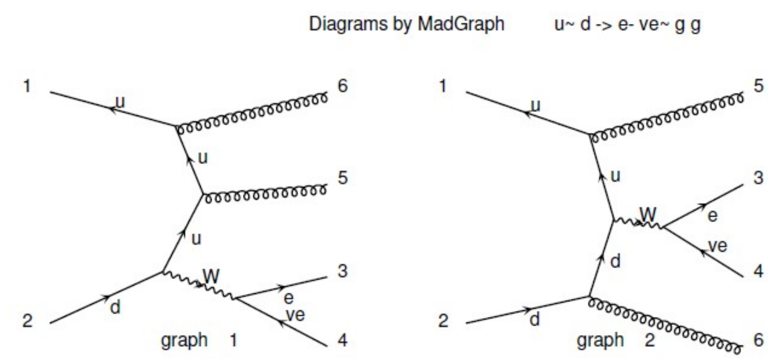
- Transfer functions go from measured quantities to parton-level information
- Lepton: assume energy and angles measured exactly
- Jets: assume angles measured exactly, define double Gaussian transfer function between jet and parton energies
- Neutrino: calculate transverse momentum at each step of parton integration; integrate over all possible values of z-momentum



Matrix elements

- MadGraph used for the calculation
- Calculate matrix elements for WW, WZ, Wgg, Wgj, Wbb, Wcc, Wcg, and single top
- No explicit calculation for Z+jets, $t\bar{t}$, or QCD multi-jet background
  - These require some treatment (additional integration) associated with missing or mis-ID'ing a jet or lepton





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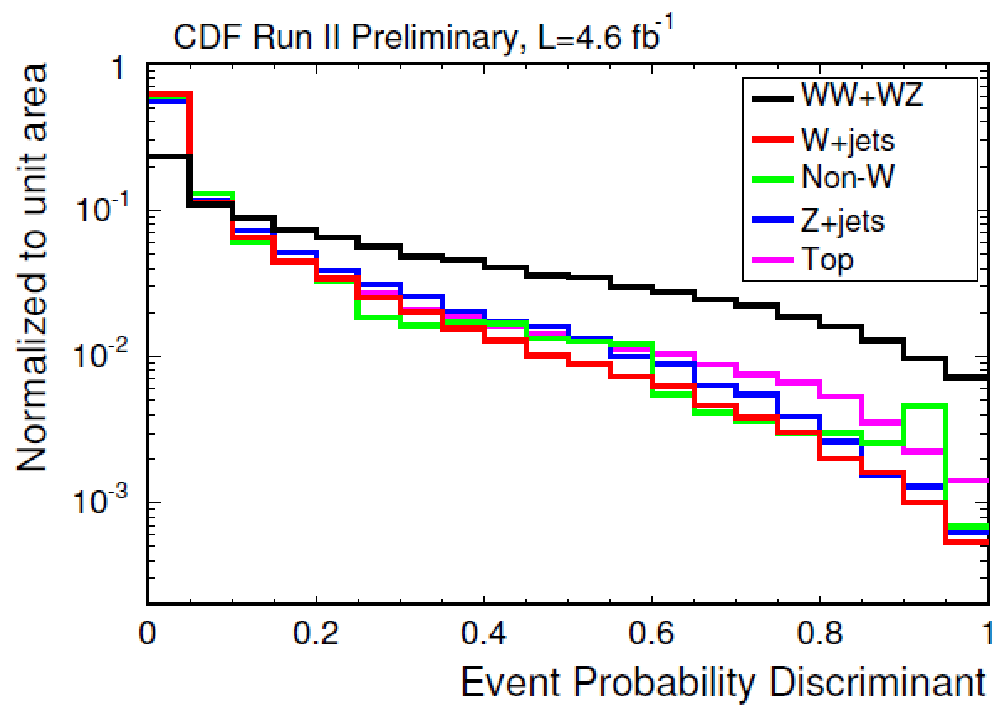
Discriminant

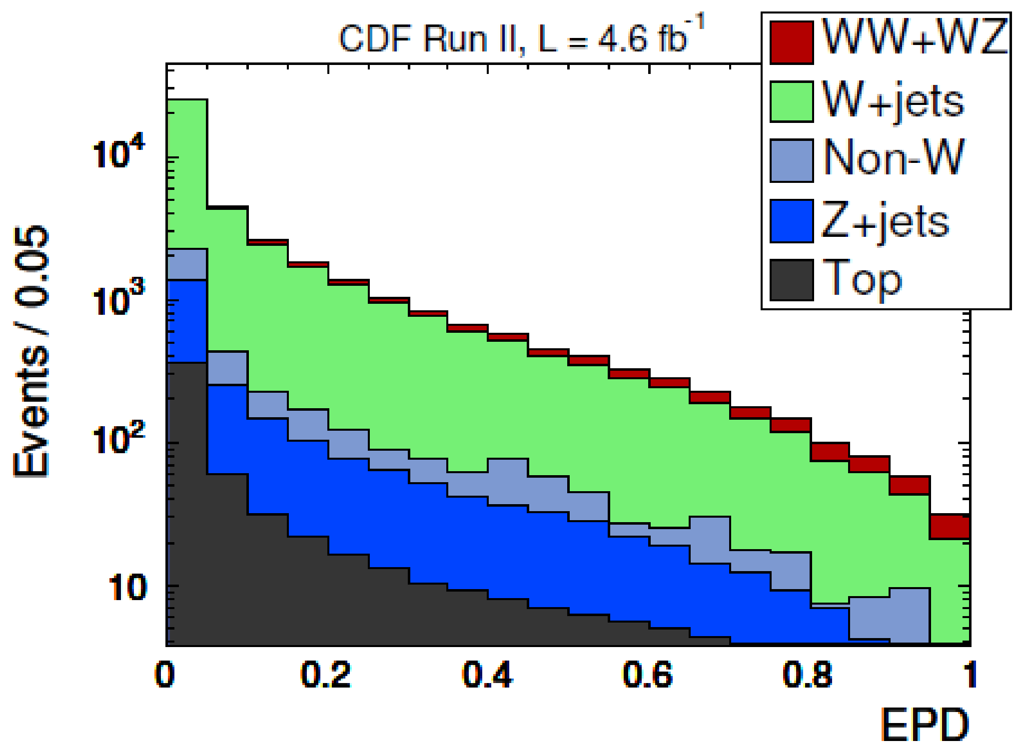
- The "probabilities" are turned into a discriminant (Event Probability Discriminant or EPD)
- EPD = $P_{sig} / (P_{BG} + P_{sig})$
  - $P_{sig} = P_{WW} + P_{WZ}$
  - P_{BG} = sum of probabilities of BG processes
- Some optimization of this discriminant to give greatest difference in shape between signal and background
  - Coefficient in front of probability for each process



- Signal does not peak at 1
  - Background events often look signal-like and signal events often look background-like
- Difference in shape is still usable

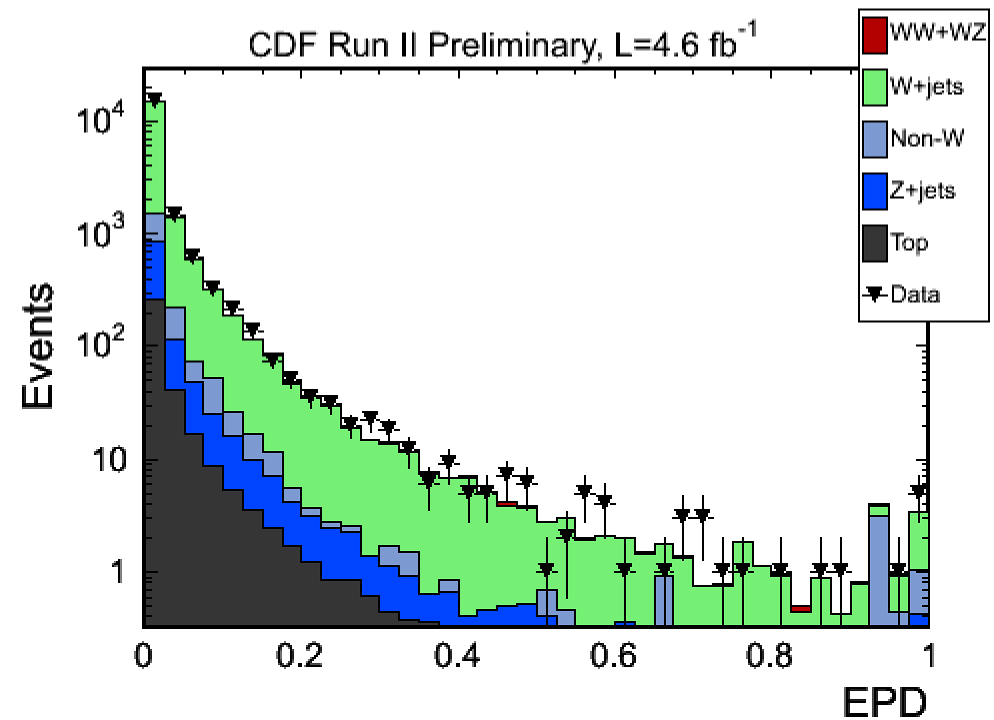
Discriminant (II)

Stacked templates

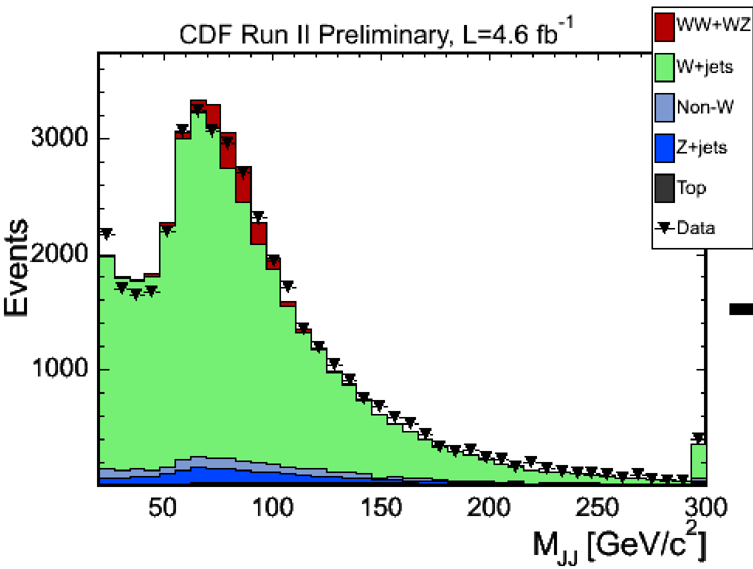


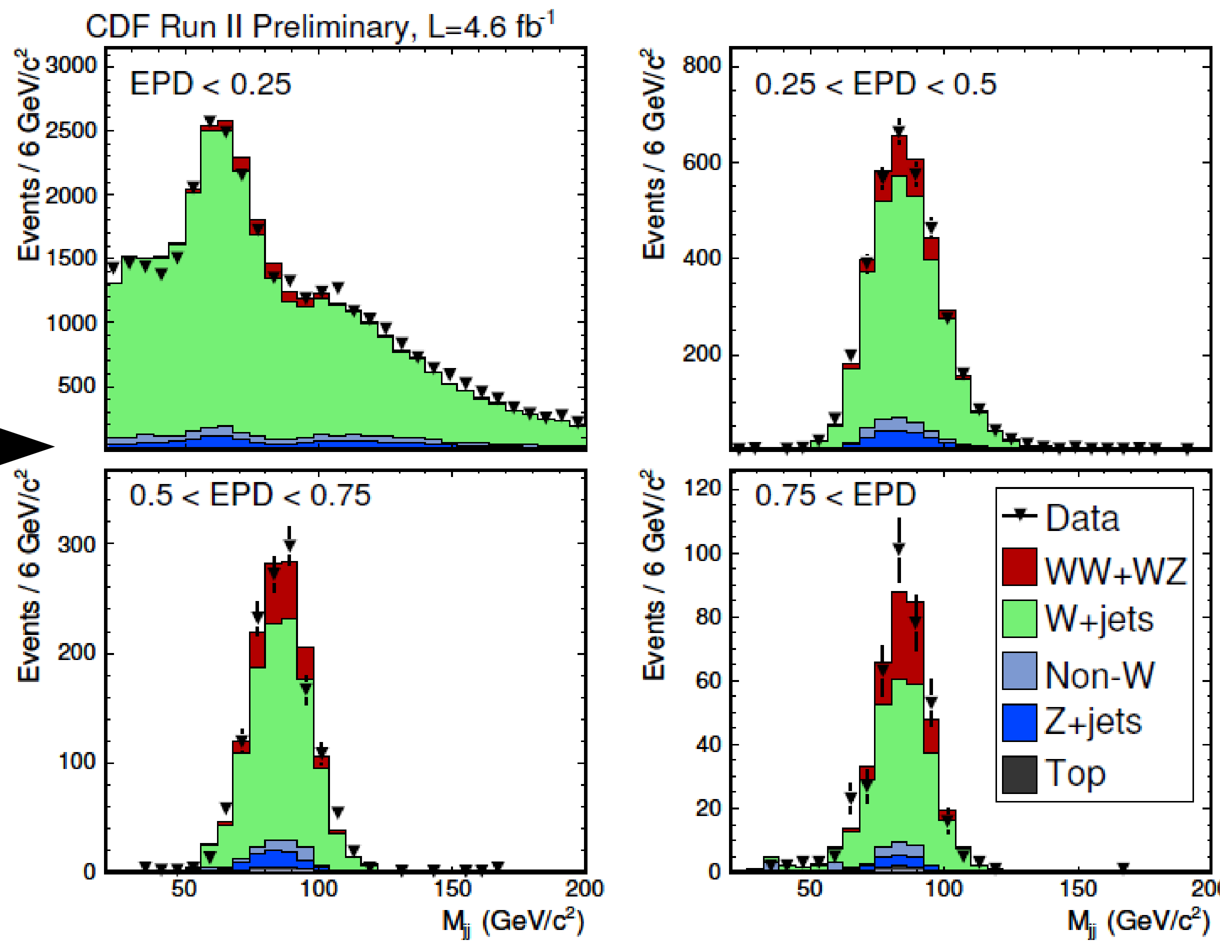
EPD for data and MC in "control regions"

Mjj < 55 and Mjj > 120

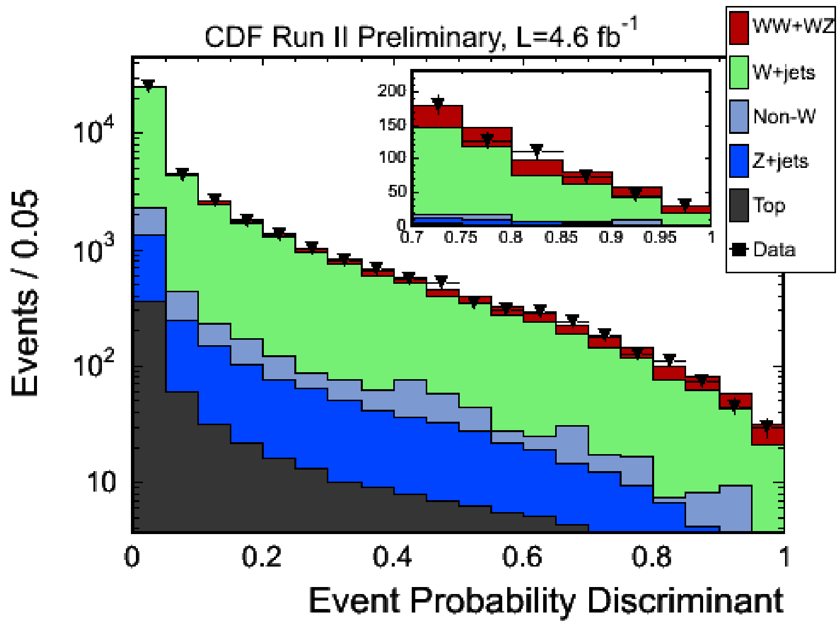


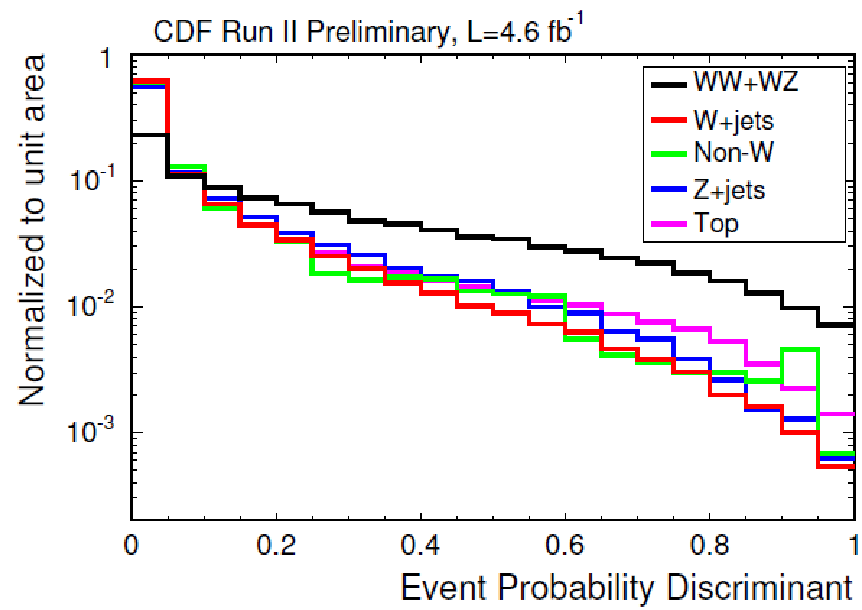
Effectiveness of the EPD





Extracting the cross section





- Fit EPD shape in data with sum of templates from models
  - Binned maximum likelihood fit
- W+jets normalization very well constrained by first bins

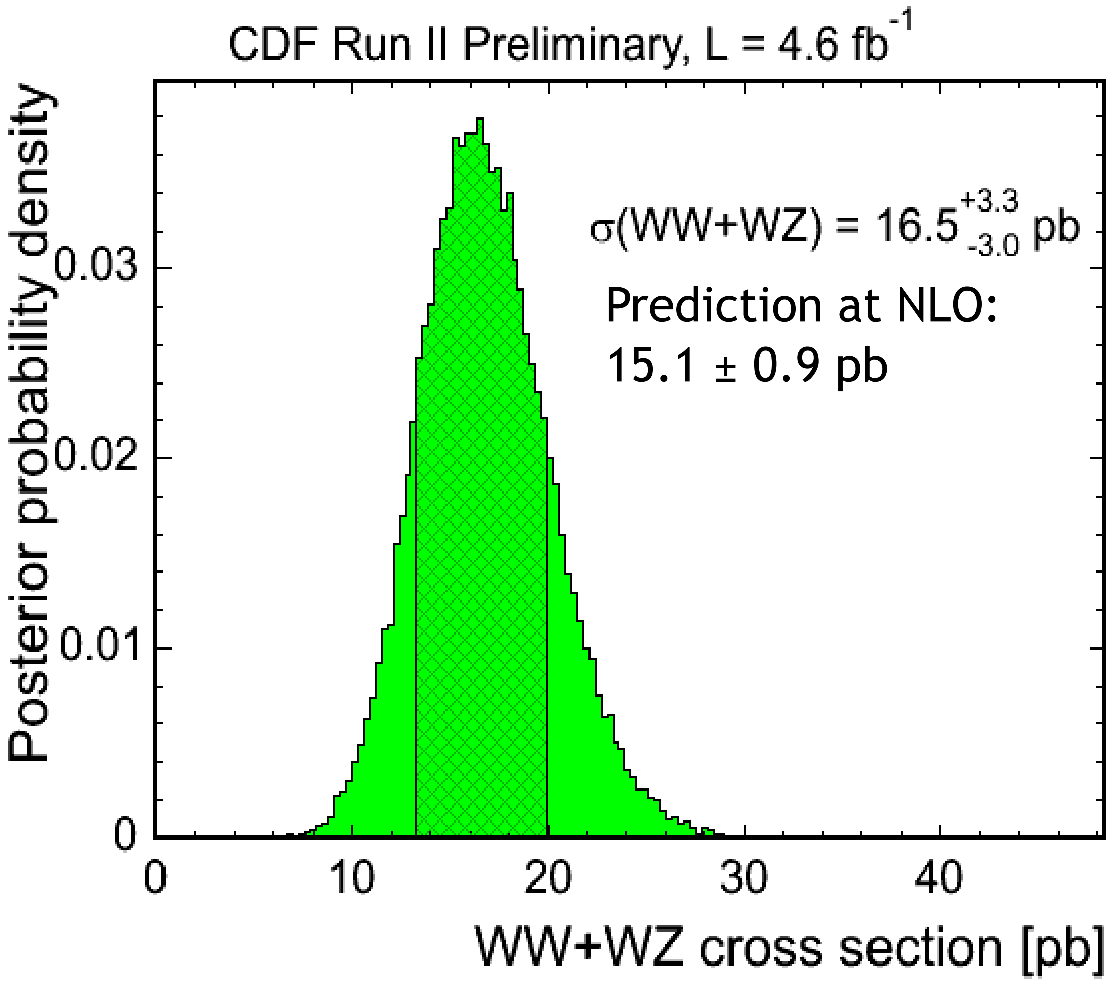
Systematic uncertainties

- *Signal normalization (acceptance)*
  - Initial and final state radiation
  - Parton distribution functions
  - Jet energy scale
  - Integrated luminosity
  - Trigger / ID efficiencies
- *Signal shape*
  - Jet energy scale
- *Background normalization*
  - Integrated luminosity
  - Trigger / ID efficiencies
  - Theoretical cross sections
- *Background shape*
  - JES
  - Q^2 scale
  - Mismodeling of p_{Tjj}

Source	Expected contribution WW+WZ cross section uncertainty
Statistics	14%
JES	8%
Q^2	7%
ISR / FSR	4%
Luminosity	6%
JER	small
p_{Tjj} mismodeling	small
PDFs	small
Efficiency	small
Total systematics	16%
Total	21%

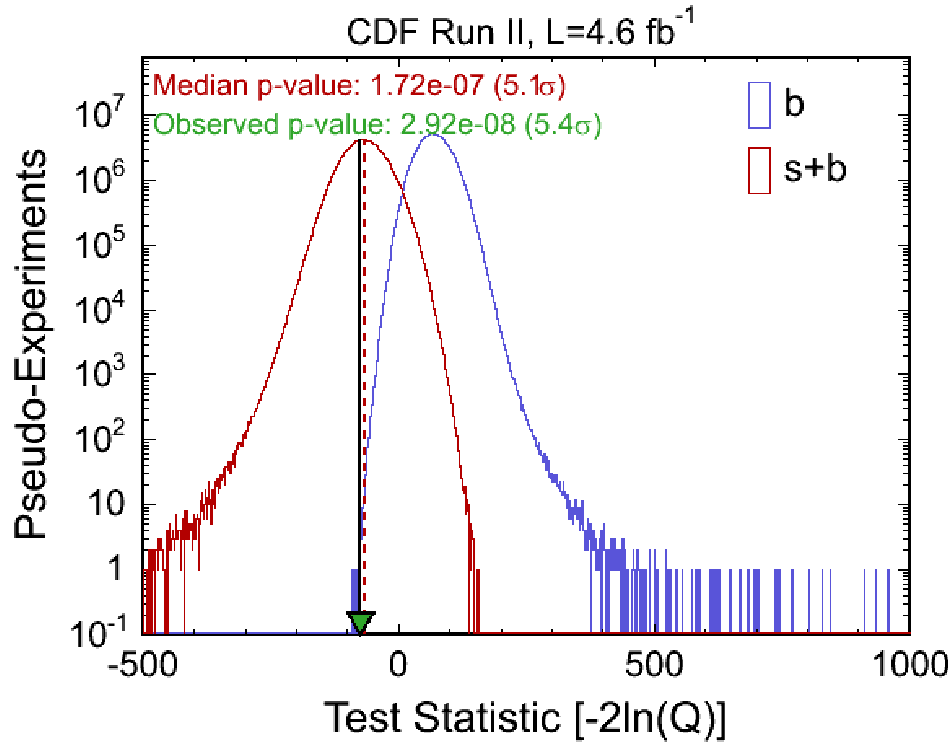
Systematic uncertainty is larger than statistical

Result: cross section



p-value calculation

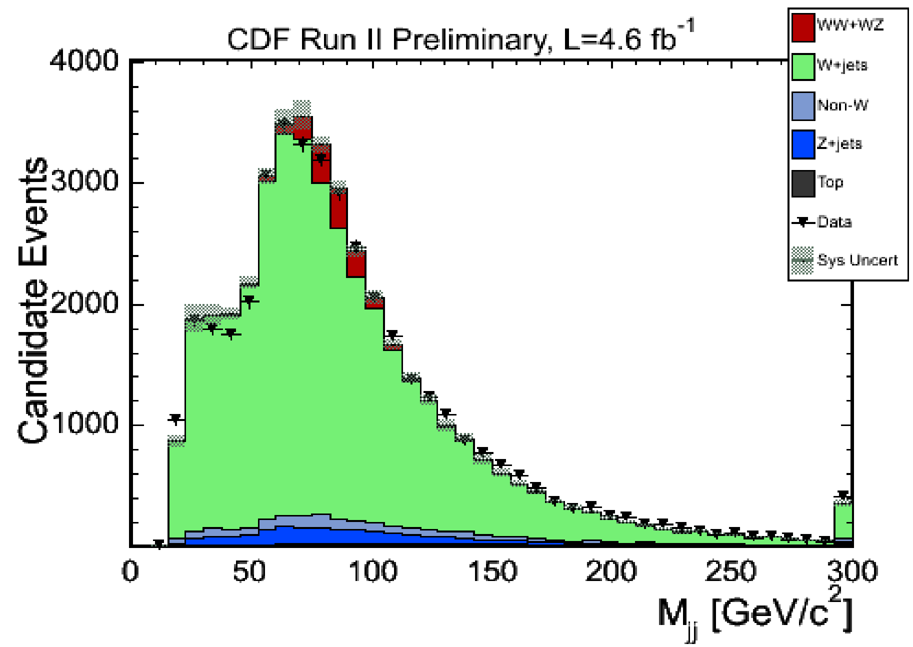
- Does signal represent significant deviation from model with σ(WW+WZ)=0?
  - Test signal+background (*s*+*b*) hypothesis and background-only (*b*) hypothesis
- Define test statistic as likelihood ratio, Q=L(*s*+*b*)/L(*b*)
- Generate pseudo-experiments for *s*+*b* and *b* hypotheses
  - Systematic uncertainties taken into account by varying them in each pseudo-experiment



- Expected *p*-value: 5.1σ (probability that a *b* pseudo-experiment is more signal-like than the median *s*+*b* pseudo-experiment)
- Observed *p*-value: 5.4σ (probability that a *b* pseudo-experiment is more signal-like than the data)

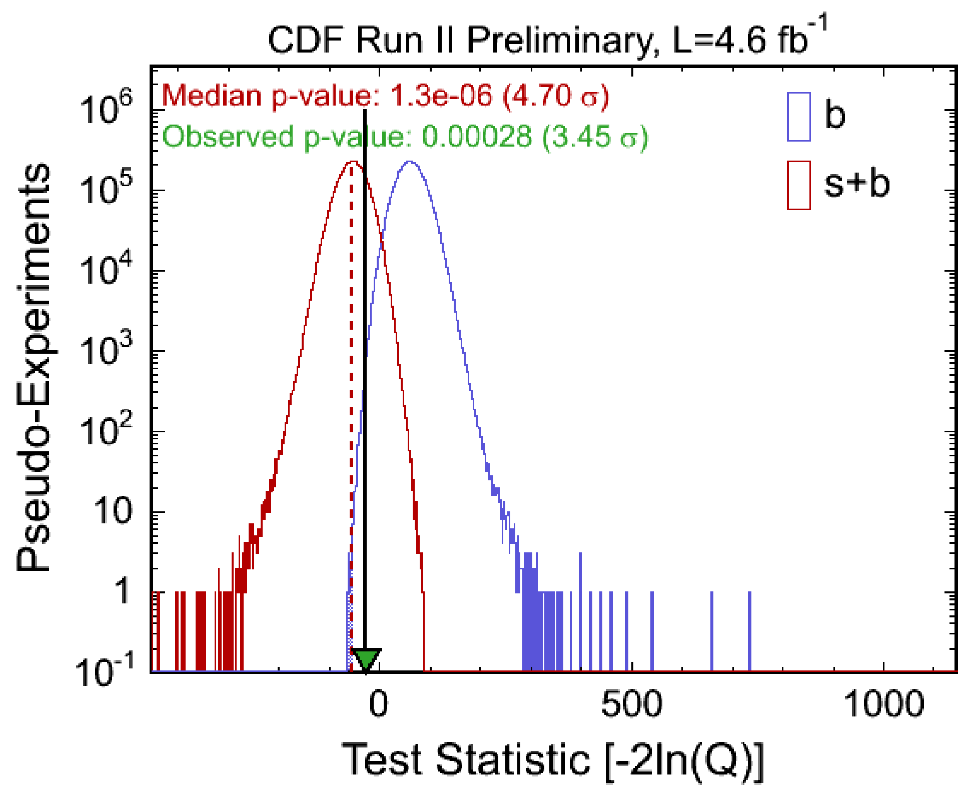
What about fitting the dijet mass?

- "Simpler" analysis: actually just more intuitive quantity
- Identical treatment of event selection, systematic uncertainties, and fit as in matrix element analysis
- Effect of systematic uncertainties in cross section extraction very different
  - JES and Q^2 constrained by fit → smaller uncertainties when fit to M_{jj} than ME
  - Uncertainty due to p_{Tjj} mismodeling is larger



Results with dijet mass

- Expected results
  - Sensitivity: 4.6σ (5.1σ with ME)
  - Cross section uncertainty: 19% (21% with ME)
- Observed results
  - σ(WW+WZ) = $11.8^{+3.0}_{-2.7}$ pb
  - Significance: 3.5σ



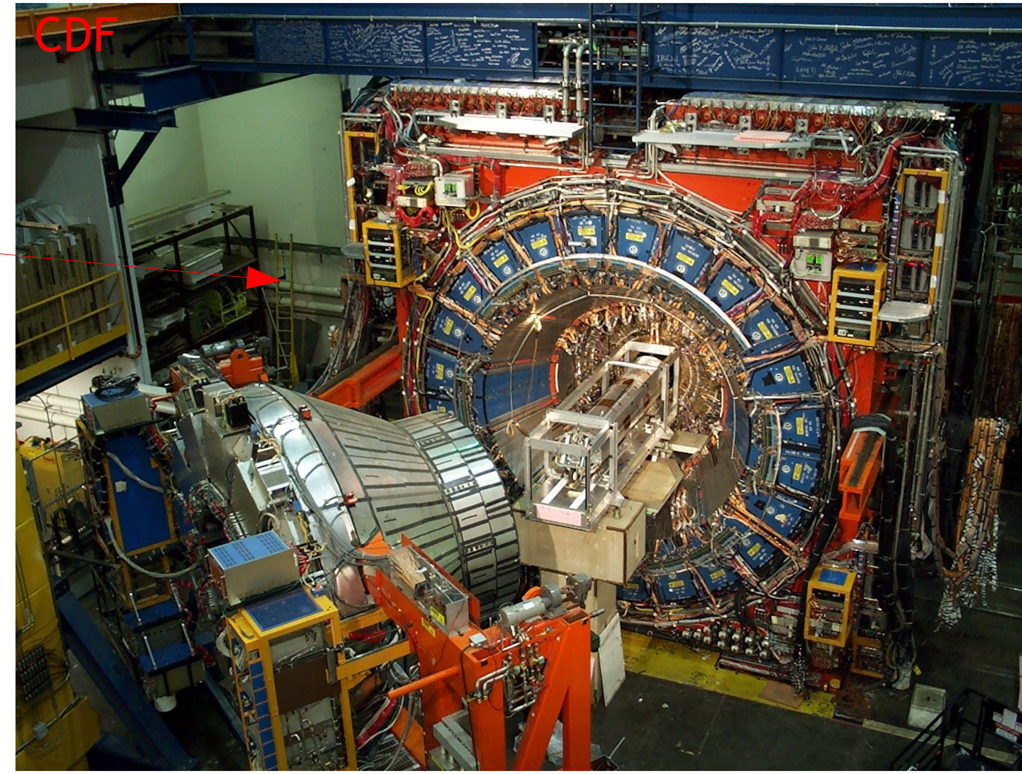
Matrix element	Dijet mass	Theory (NLO)
$16.5^{+3.3}_{-3.0}$ pb	$11.8^{+3.0}_{-2.7}$ pb	15.1 ± 0.8 pb

Conclusions

- We have observed WW+WZ → lvjj and measured the WW+WZ production cross section
  - Technique based on matrix element calculations gives sensitivity needed for observation
  - Signal significance: 5.4σ
  - $\sigma(p\bar{p} \rightarrow WW+WZ) = 16.5^{+3.3}_{-3.0}$ pb
- Measurement is already systematically limited
- Measurement with dijet mass is compatible with ME result
  - Less sensitive, but smaller cross section uncertainty
- Continued progress towards Higgs!
  - WW+WZ observation is validation that we can find small signal in large backgrounds with sophisticated analysis
  - Analysis improves understanding of backgrounds and systematics for WH → lvbb

Backup

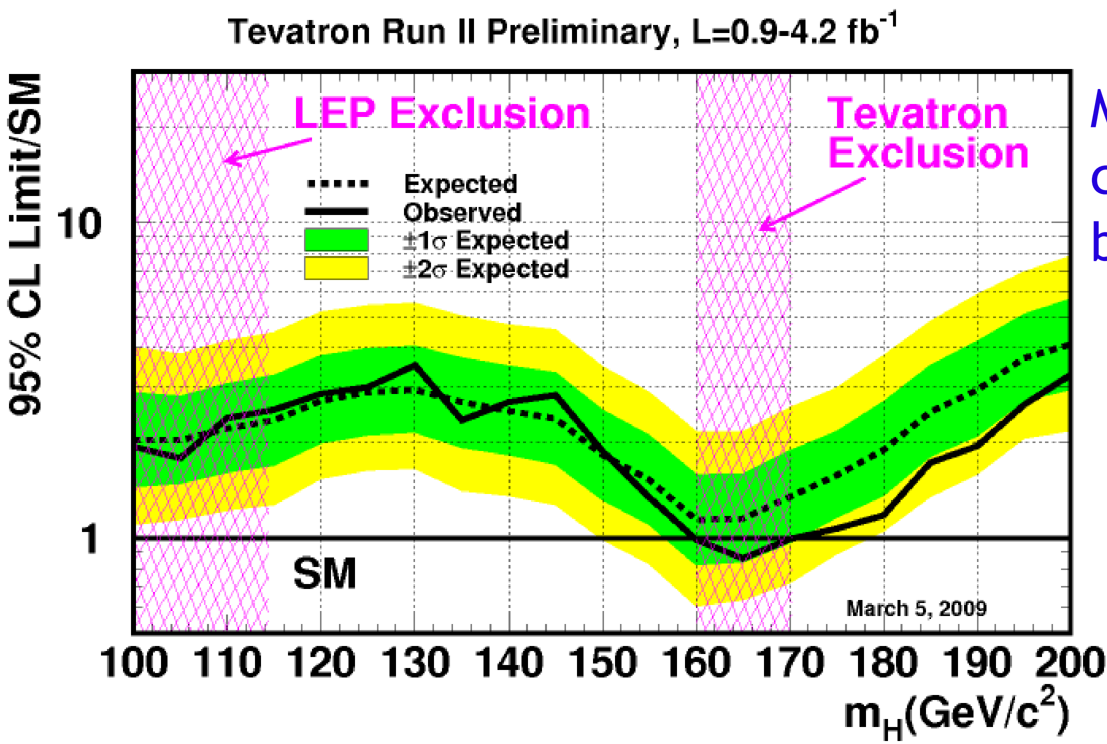
CDF at the Tevatron



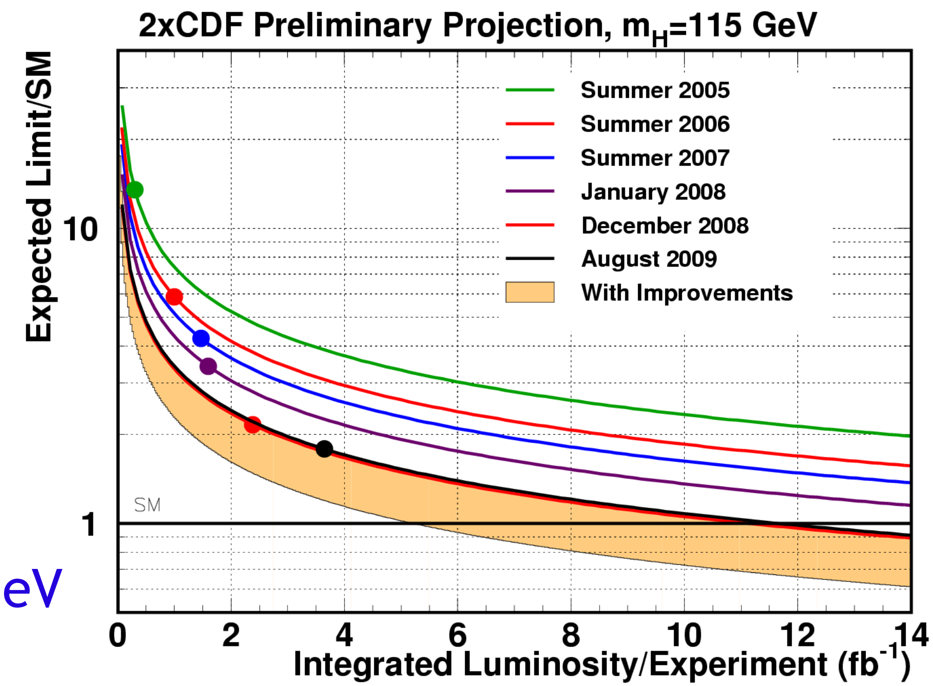
- $p\bar{p}$ collider at $\sqrt{s}$ = 1.96 TeV
- Recent stable operation with increasing instantaneous luminosity

- Collider detector:
  - Charged particle tracking
  - Electromagnetic and hadronic calorimetery
  - Muon system

Higgs searches at the Tevatron

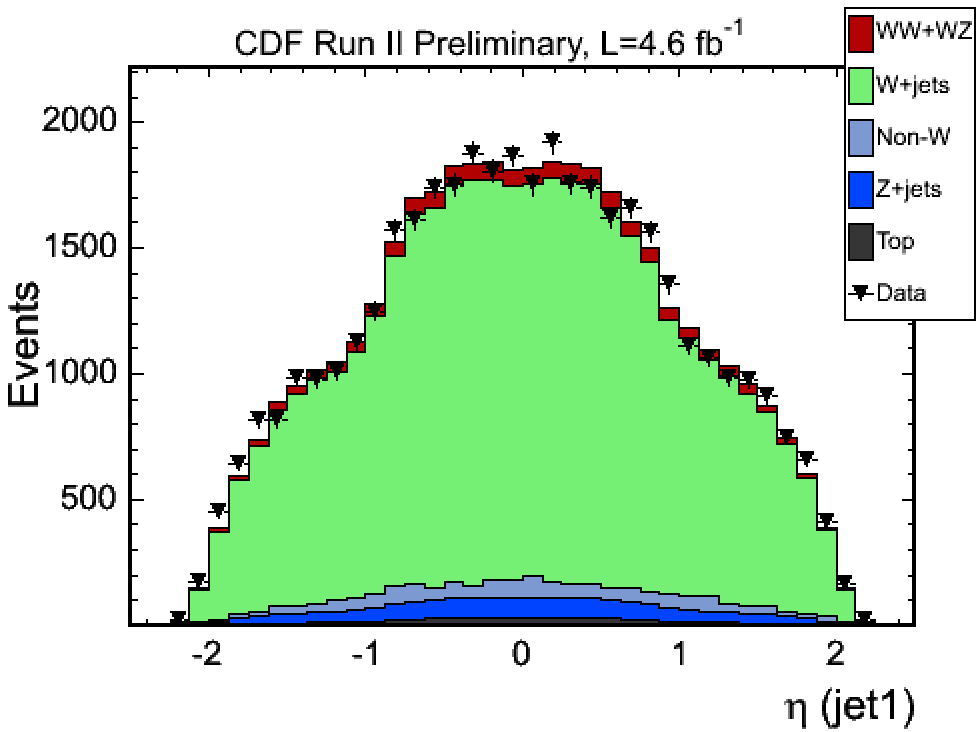


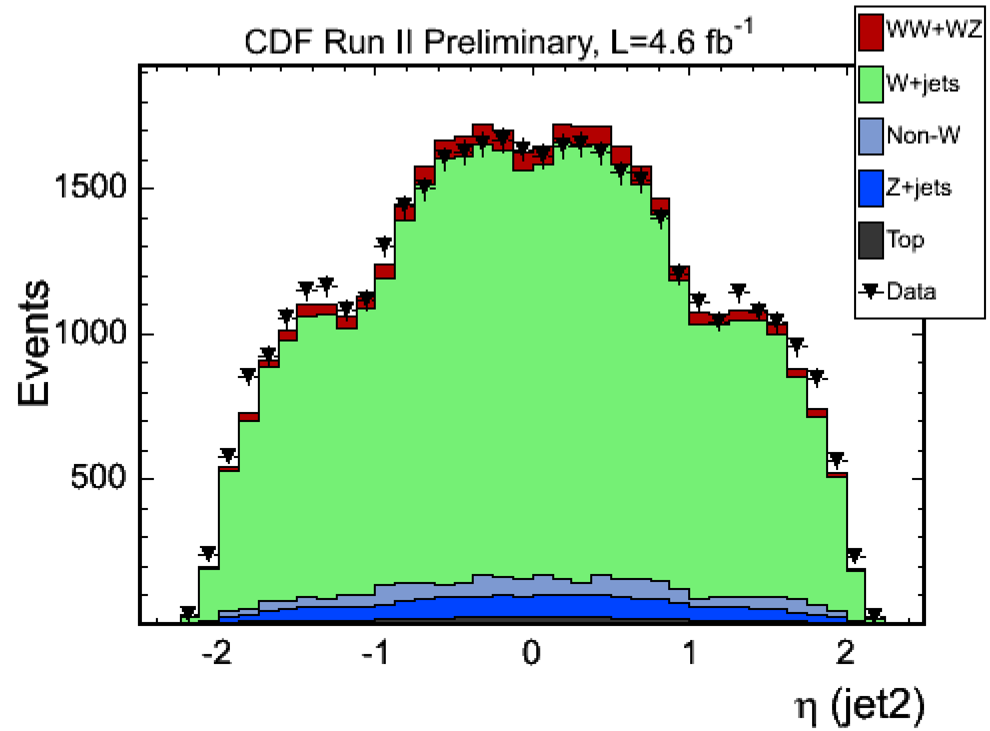
March 2009: Exclusion at 95% confidence level of Higgs boson for $160 < M_H < 170$ GeV



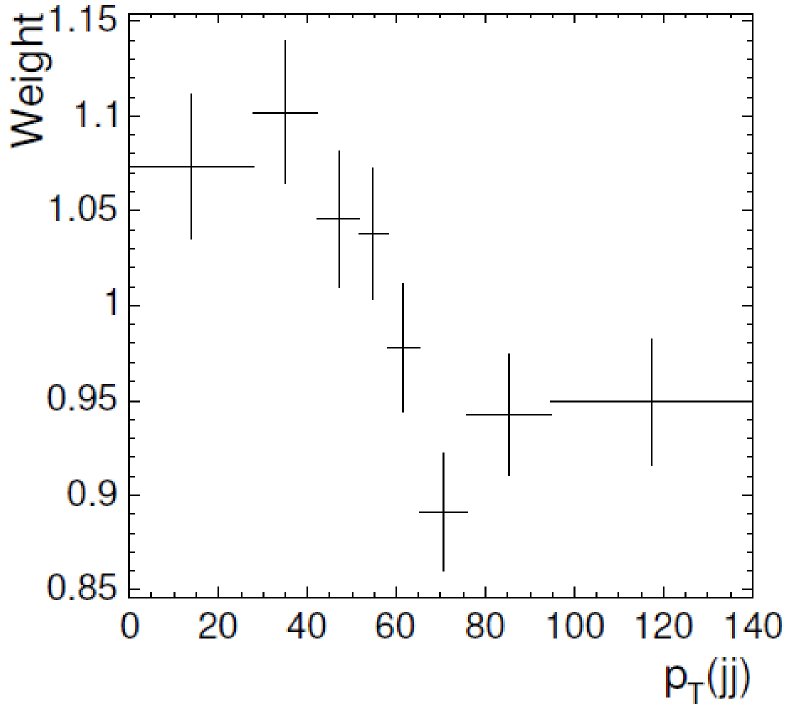
With expected future datasets and improvements in analyses, could reach Standard Model sensitivity for M_H = 115 GeV

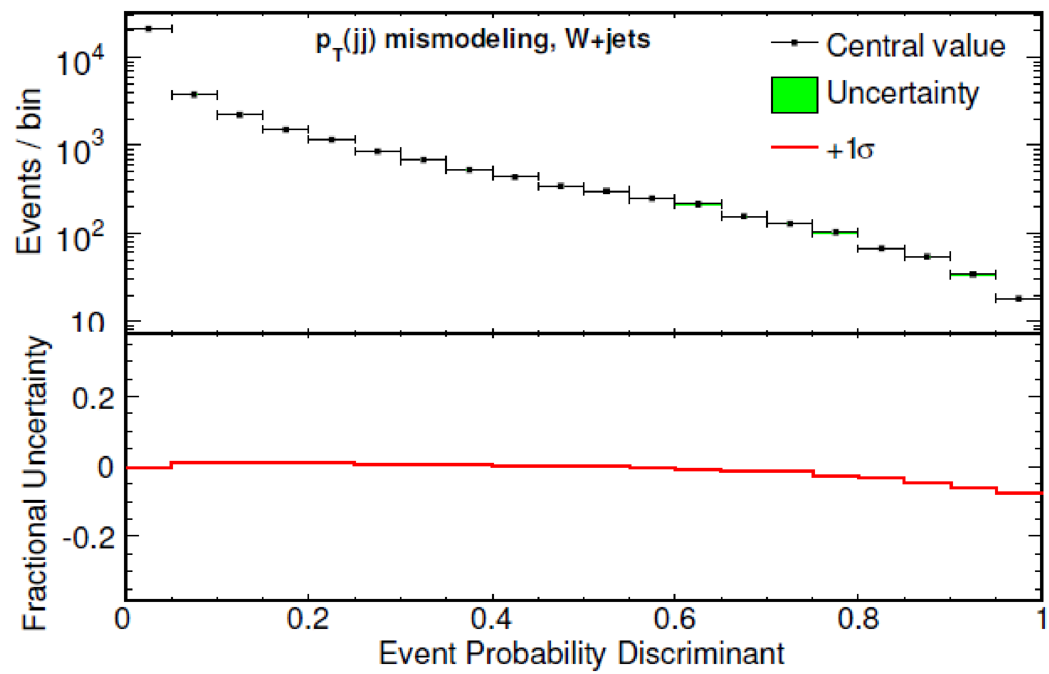
Jet eta


CDF Run II Preliminary, L=4.6 fb^{-1}
WW+WZ
W+jets
Non-W
Z+jets
Top
Data
Events
2000
1500
1000
500
-2
-1
0
1
2
η (jet1)

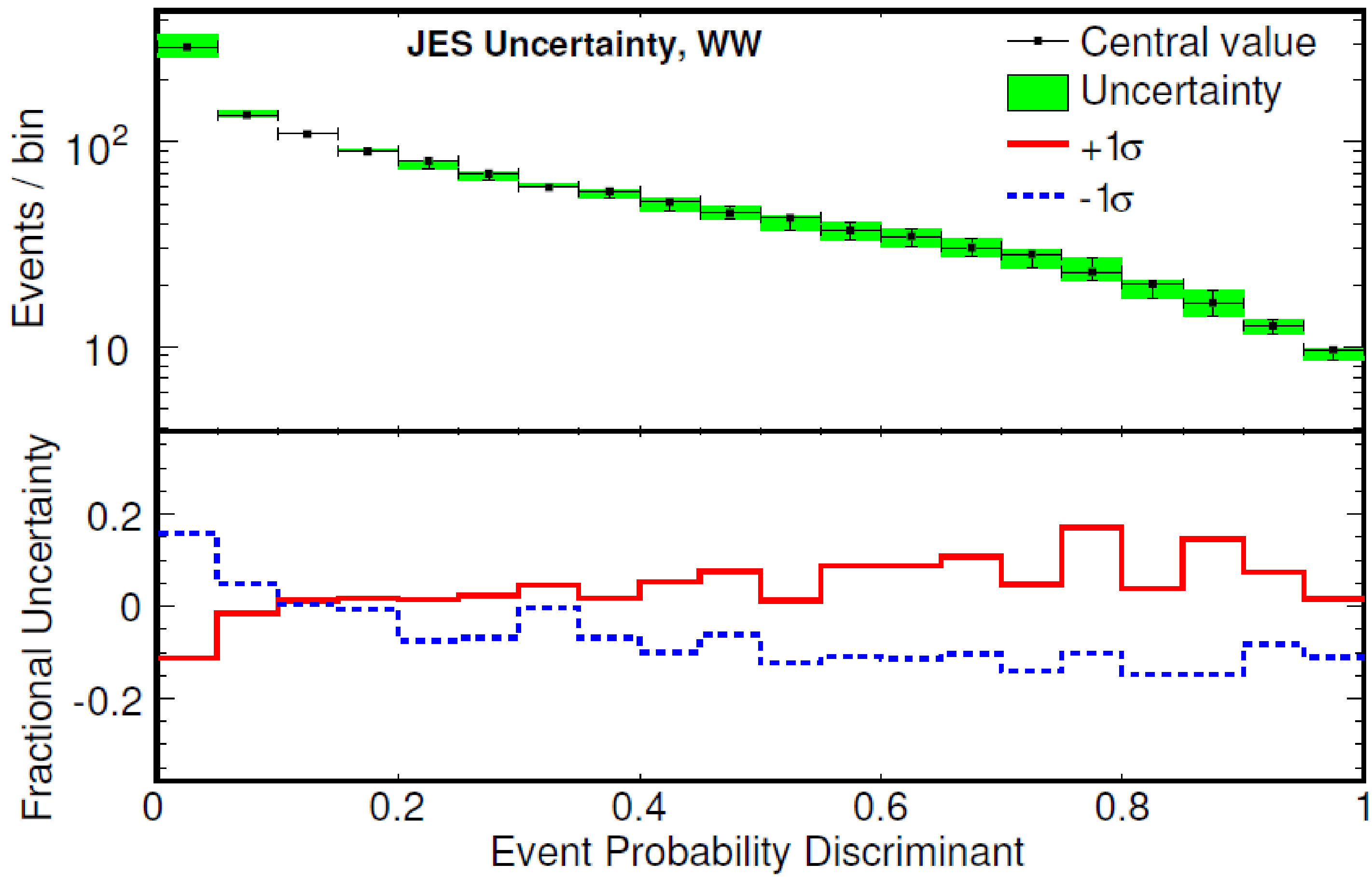

CDF Run II Preliminary, L=4.6 fb^{-1}
WW+WZ
W+jets
Non-W
Z+jets
Top
Data
Events
1500
1000
500
-2
-1
0
1
2
η (jet2)

Mismodeling shape systematic

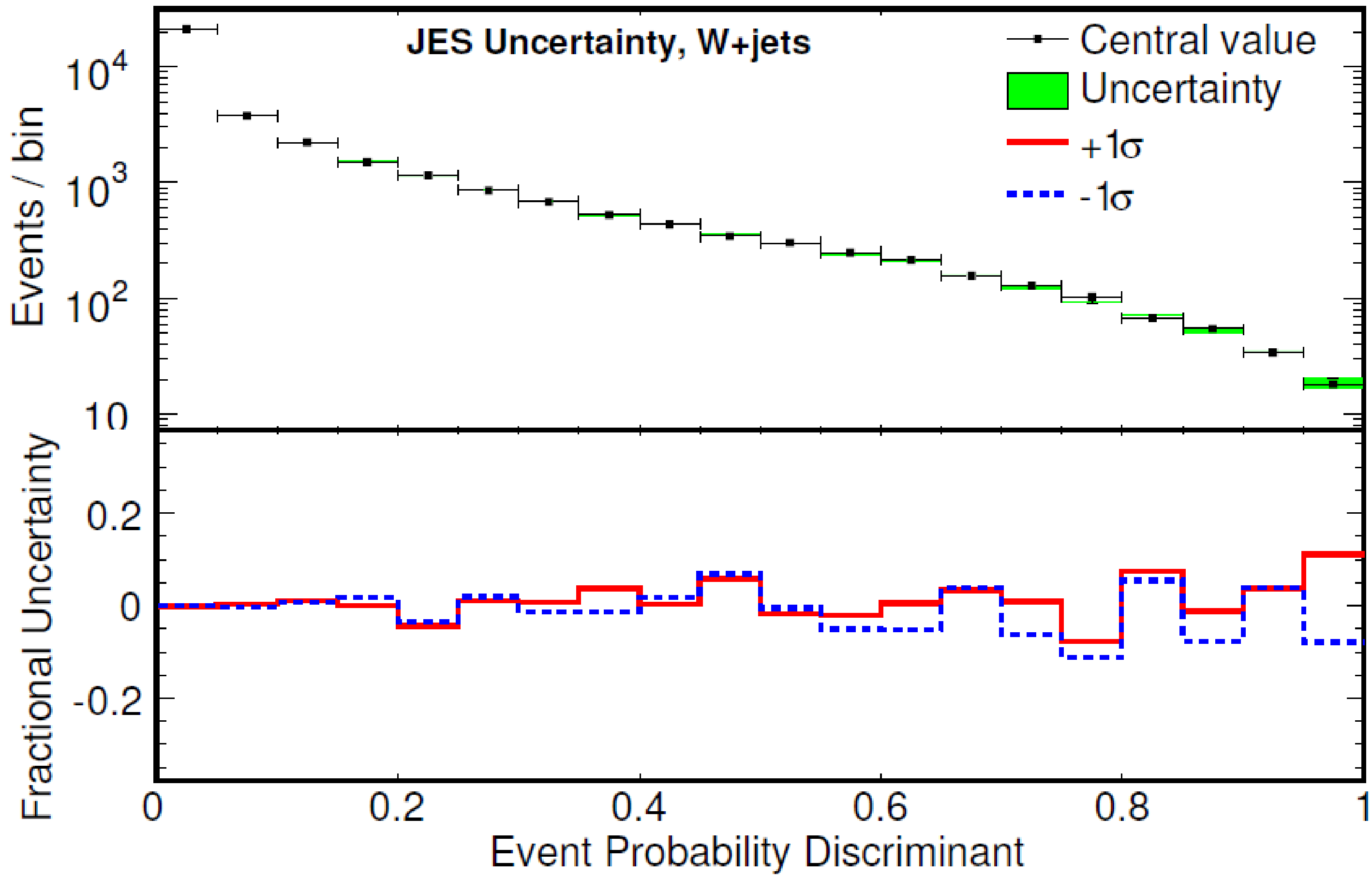




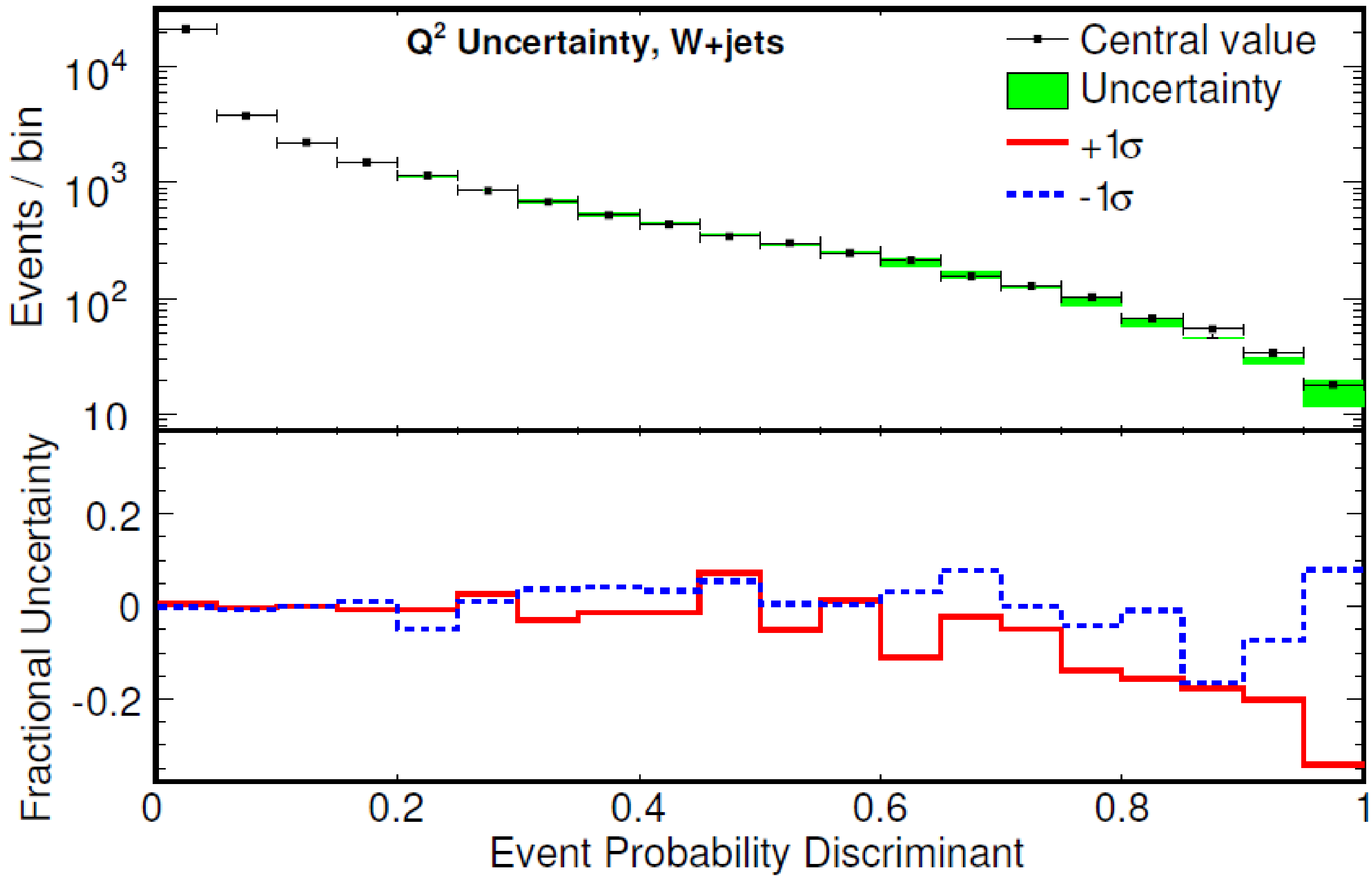
JES uncertainty, WW



JES uncertainty, W+jets

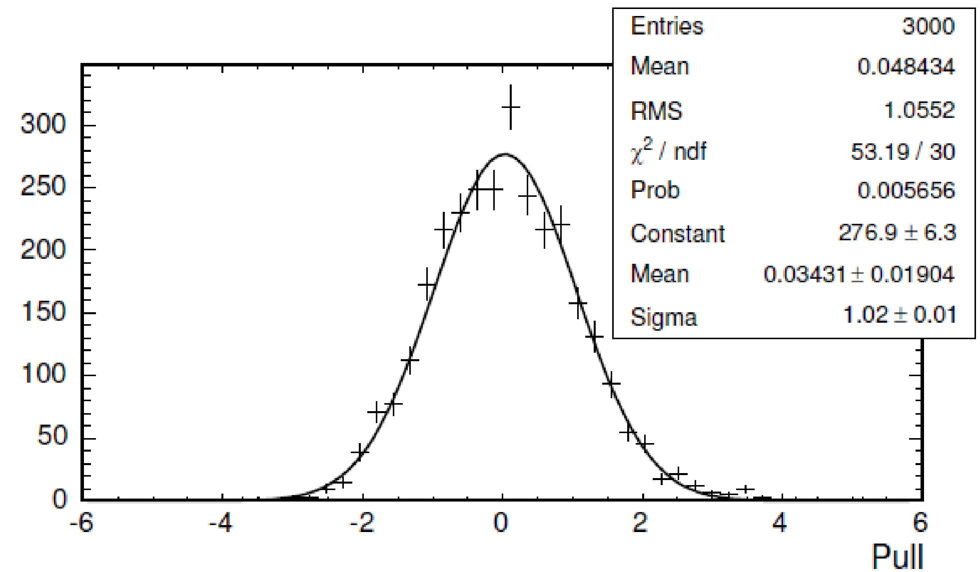


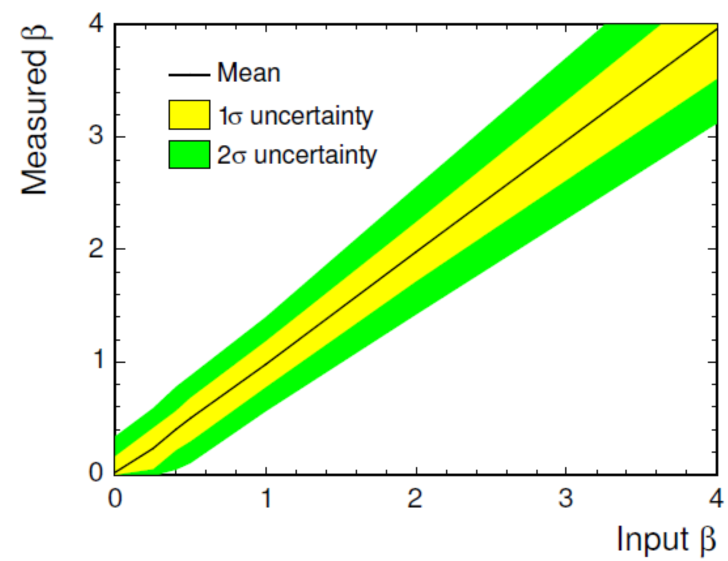
Q^2 scale uncertainty



Likelihood fit to extract cross section

- Bayesian fitting procedure
  - Systematics treated as nuisance parameters, integrated over in likelihood function
  - Flat prior p.d.f. in WW+WZ cross section
  - Nuisance parameters have Gaussian priors
- Pseudo-experiments with various expected WW+WZ cross sections as input
  - Fit has linear behavior, expected pull distribution



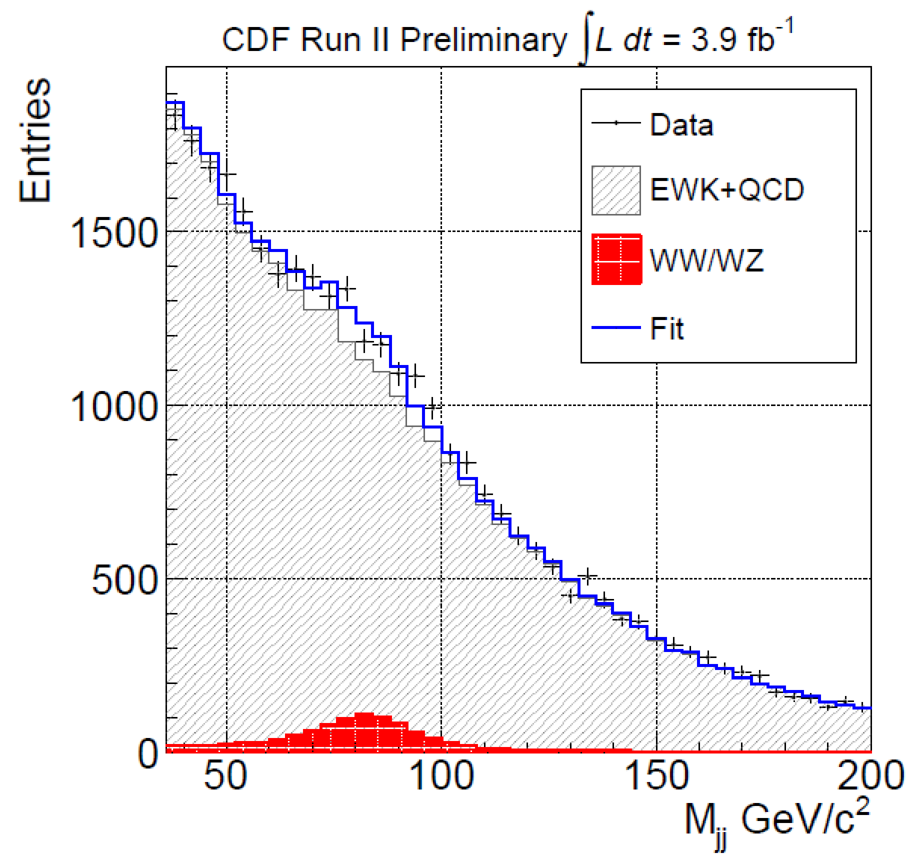


Result in channels

Central electrons	Central muons	Extended muons
$15.9^{+4.2}_{-4.5}$ pb	$19.8^{+3.3}_{-5.4}$ pb	$10.7^{+7.6}_{-5.4}$ pb

Another CDF measurement

- Using lower pT cuts on leptons, and imposing pTjj > 40 GeV, have smoothly falling dijet mass distribution in backgrounds
  - Can see peak in data
- Cross section measurement is compatible with our result
- Difficult to compare details with our analysis
  - Only ~30% overlap in signal samples
  - Different fitting procedures



ATLAS work

ATLAS work: tile calorimeter

- Testbeams
  - Took shifts in 2003 and 2004
  - Analysis of standalone (only TileCal) testbeam in 2003 found ~1.4% module-to-module uniformity of response to hadrons
    - Public ATLAS note: ATL-TILECAL-PUB-2006-008
    - Included in NIM paper: *Testbeam studies of production modules of the ATLAS Tile Calorimeter,* Nucl. Instr. and Meth. A606, 362 (2009).
  - Contributed to analysis of combined (full slice of ATLAS) testbeam in 2004
    - NIM paper: *Study of the response of the ATLAS central calorimeter to pions of energies from 3 to 9 GeV,* Nucl. Inst. and Meth. A607, 372 (2009).
- Charge injection calibration system
  - Careful investigation of properties of TileCal electronics
    - ATLAS note: ATL-TILECAL-INT-2008-002

ATLAS work cont'd

- In charge of TileCal "data" quality validation 2005-2006
  - Part of commissioning calorimeter *in situ* after its move into the cavern
- Studied use of photon-jet events for establishing jet energy scale and its systematic
  - Included in CSC book: G. Aad, et al., *Expected Performance of the ATLAS Experiment : Detector, Trigger and Physics*, arXiv:0901.0512 ; CERN-OPEN-2008-020.
  - ATLAS note: ATL-PHYS-INT-2009-014
- Preparation of differential dijet mass cross section measurement
  - Studied sensitivity to quark compositeness with early data